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# MATHEMATICAL MODEL STUDIES OF WATER QUALITY IN THE POTOMAC ESTUARY

Leo J. Clark, et al

Environmental Protection Agency
Annapolis, Maryland

March 1972

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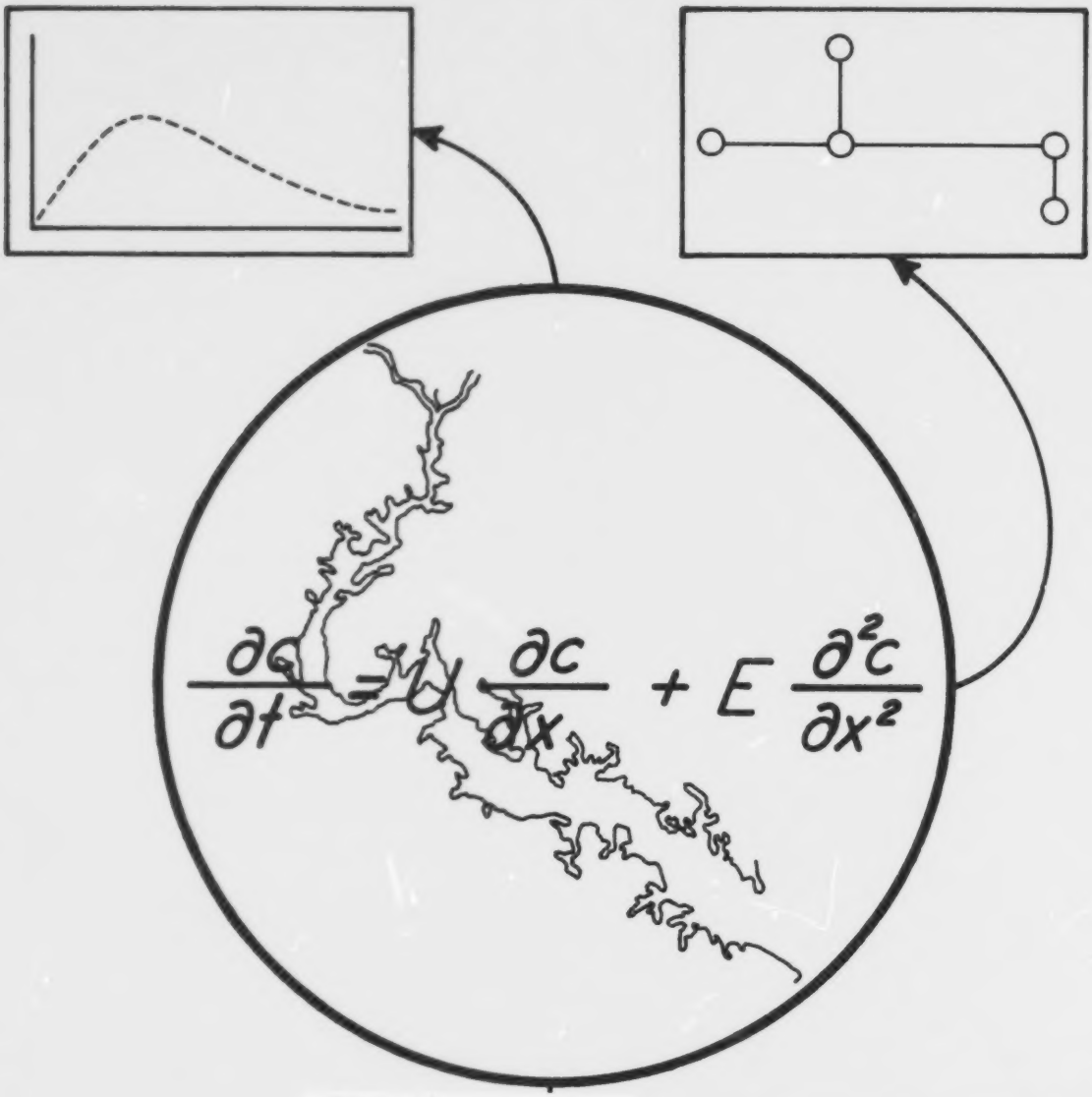


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TECHNICAL REPORT 33
ENVIRONMENTAL PROTECTION AGENCY
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MARCH 1972

Annapolis Field Office
Region III
Environmental Protection Agency

# MATHEMATICAL MODEL STUDIES OF WATER QUALITY IN THE POTOMAC ESTUARY

Technical Report 33

March 1972

Leo J. Clark

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## PREFACE

During 1969, two independent but coordinated studies were undertaken by the U. S. Department of the Interior, (FWQA)* and the Corps of Engineers to ascertain the feasibility of using the upper Potomac Estuary as a supplemental water supply source for the Washington Metropolitan Area. Another of the primary requirements for the FWQA study was determination of maximum allowable pollutant loadings to achieve and maintain the adopted water quality standards. Current water quality conditions in the upper estuary have been adequately defined by extensive sampling, but prediction of the effects of large freshwater withdrawals and the corresponding increases in wastewater flows on water quality was also required.

The Chesapeake Technical Support Laboratory (CTSL)** has employed mathematical modeling techniques to predict water quality behavior in the Potomac Estuary for various hydraulic conditions and wastewater loading schemes. While existing estuary models have proven to be flexible and versatile tools, verification for a particular system was necessary before reliable predictions could be made. This report presents CTSL's findings based upon simulation studies in the Potomac Estuary using two of the more commonly known mathematical models: (1) DECS III***, and (2) the FWQA Dynamic Estuary Model. The former model employs an average tidal solution whereas the latter is based upon a real-time solution.

* Now the Environmental Protection Agency
** Presently known as Annapolis Field Office
*** Hereafter referred to as the Thomann Model

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# CHAPTER I

# INTRODUCTION

## A. PURPOSE AND SCOPE

Mathematical models are becoming an increasingly important "tool" for predicting, under a variety of conditions, water quality behavior in an estuary. The purpose of this report is to present recent CTSL studies on use of these models in the Potomac Estuary, specifically, the Thomann Model (time-dependent version) and the FWQA Dynamic Estuary Model.

Numerous computer runs were made with both models in an attempt to make a reasonably accurate simulation of dye profiles observed in the Potomac Estuary following a 13-day continuous release during November 1969 and of observed dye profiles in the Anacostia River following a 7-day continuous release during April 1970. In addition to model verification, consideration was given to: (1) a comparison of modeling approaches, (2) the limitations of each model, (3) input data requirements, and (4) a detailed sensitivity analysis to determine which input parameters had the greatest effect on model output. Hopefully, investigations of each of these factors will assist in future modeling efforts by defining the limitations and applicability of each model and also by indicating where expenditures for necessary data refinement are warranted.

While mathematical models have been developed for the entire Potomac Estuary, most studies in this report pertain to the 40-mile reach of the upper estuary extending from Key Bridge to Sandy Point (Figure I-1).

# POTOMAC ESTUARY

FIGURE I-1

B. ACKNOWLEDGEMENTS

The assistance and cooperation extended by the personnel at the District of Columbia's Blue Plains Sewage Treatment Plant, the Washington Suburban Sanitary Commission, and the U. S. Geological Survey, Washington, D. C. contributed to successful completion of this study and is gratefully acknowledged.

# CHAPTER II

## SUMMARY AND CONCLUSIONS

In its continuing study of the Potomac Estuary, the Chesapeake Technical Support Laboratory (CTSL) has utilized mathematical models to predict water quality response to given hydrographic, demographic, and other physical, chemical, and biological constraints. In the course of model application, many problems associated with verification became evident almost immediately. The findings and conclusions which evolved during CTSL verification studies of both a nontidal model (Thomann) and a tidal or real-time model (FWQA Dynamic Estuary) for the Potomac are reported as follows:

1. The primary model verification effort involved simulation of a 13-day continuous dye release during November 1969 in which 4,454 pounds of diluted (6 percent) Rhodamine WT dye were discharged into the Potomac Estuary at the District of Columbia's Blue Plains Sewage Treatment Plant.

2. Using dispersion coefficients varying from 2.0 $mi^2/day$ to 5.0 $mi^2/day$, the Thomann Model appeared to simulate the 1969 Potomac dye study satisfactorily in terms of peak concentrations and longitudinal dye distribution. Shortcomings found in the Thomann Model simulations were pronounced "peaking" during the early phase of the release and insufficient movement of peak dye concentration. Both of these problems were probably caused by the basic analytical (nontidal) solution employed by this model since refinement in the segmentation did not appear to overcome them.

3. A comparison of observed spatial profiles and those obtained from the Dynamic Estuary Model indicated that, except for minor differences in peak dye concentrations near the release point and the rate of downstream transport, the Dynamic Estuary Model was also adequately verified using the 1969 Potomac dye study data. For this verification, the dispersion coefficient ranged from about 1.0 to 2.0 $mi^2$/day depending on the existing tidal velocities and depths.

4. In order to define the mass transport characteristics of the Anacostia Tidal River better and also to provide data upon which confirmation of dispersion rates and other model input for this tidal system could be based, a 7-day continuous dye release was conducted during April 1970 at the Bladensburg Marina, above the D. C.-Maryland line.

5. With the exception of inadequate downstream movement of the simulated peak concentration, both the Dynamic Estuary and Thomann Models appeared to be capable of closely predicting the observed dye distribution in the Anacostia River.

6. A Potomac dye study conducted in 1965 was successfully simulated with both the Dynamic Estuary and Thomann Models. The substantially lower freshwater inflows which occurred during this study resulted in the use of lower dispersion coefficients (1.0 - 2.0 $mi^2$/day) for the Thomann Model. The dispersion coefficients remained the same in the DEM.

7. Based on all of the dye simulation studies, it can be concluded from the standpoint of model verification that, in general, maximum difficulty was experienced in the immediate area of the release point. However, this could have been expected since complete mixing had not yet occurred in the prototype but had to be assumed in both of the models (neither model can treat vertical concentration gradients), and because of the difficulty in selecting representative sampling points.

8. Chloride profiles observed in the Potomac Estuary during 1966 and 1969 were simulated using the Thomann Model. Historical station data, showing annual fluctuations in observed and predicted chlorides, indicated very good agreement when dispersion coefficients ranged between 1.5 - 14.0 $mi^2$/day during relatively low-flow periods and 2.0 - 20.0 $mi^2$/day during the higher flow periods of 1966 and when they ranged between 2.0 - 16.0 $mi^2$/day for the entire year of 1969.

9. The following conclusions can be drawn based upon the chloride simulations performed with the Thomann Model:

a. A considerable range in the dispersion coefficients can be expected where there are great salinity increases in a longitudinal direction. The pronounced gradients, rather than the actual salinity concentrations, require much larger dispersion coefficients for the Thomann Model if meaningful data are to be obtained.

b. Dependence of dispersion coefficients on freshwater inflow rates was not as evident for chloride as it was for dye simulations. In fact, an apparent anomaly appeared since maximum chloride intrusion occurred in the

Potomac Estuary during low-flow periods whereas the use of high dispersion coefficients normally associated with high-flow periods was required in the model to produce similar results. Thus, the dispersion term in the Thomann Model may have to be evaluated and related to flow in a different manner for constituents dispersing upstream than for those dispersing primarily downstream.

10. The observed chloride data, measured longitudinally during a period of relatively steady-state flow (July-December 1965), were simulated in the Dynamic Estuary Model. Special problems involving both the advection and dispersion components arose, probably as a result of the unusually high concentration gradients.

11. The following conclusions can be drawn based upon the chloride simulations performed with the Dynamic Estuary Model:

a. The dispersion term employed in the Dynamic Estuary Model ($C_4$) must be increased over an order of magnitude in the seaward portion of the model network to reflect the increasing chloride concentration gradients and to obtain sufficient mass transfer across the seaward boundary. The approximate range in dispersion coefficients used for simulation of chlorides was from 1.0 $mi^2$/day to 20.0 $mi^2$/day for representative depths and tidal velocities.

b. Determination of the proper amount of constituent advected from one node to another in the model becomes quite critical in areas with high concentration gradients. The quarter-point solution method for advective transport, which generally produces acceptable accuracy and low numerical

mixing, did not yield satisfactory comparisons for chloride simulations in the Potomac. The use of a third-point advective concentration within a given channel was found to yield more favorable results.

12. Undoubtedly, many of the difficulties associated with application of either the Thomann or Dynamic Estuary Model to simulate the movement of chlorides are the result of representing a three-dimensional stratified system with a one-dimensional model. This further points out the importance of hydrodynamic behavior and the fallacy of using a model to solve a problem for which it was not designed.

13. In order to determine where additional refinement of model input may be warranted, a detailed sensitivity analysis of several factors pertinent to the Thomann and/or Dynamic Estuary Models was performed.

14. Based upon the results of this sensitivity analysis with the Thomann Model, the following represent a listing, in decreasing importance, of the sensitivity of each variable:

a. Dispersion coefficient (K),

b. Decay rate,

c. Segmentation, and

d. Proportionality factor ($\alpha$) used for advective transport.

15. Of the various input parameters investigated for the Dynamic Estuary Model, the decay rate and the solution technique for advective transport appeared to be the most sensitive in affecting the model's predictions. With the exception of simulating salinity (chlorides), the least sensitivity was identified with the dispersion coefficient.

While the hydraulic solution was relatively sensitive to the Manning roughness coefficients, the quality predictions were insensitive to them as well as to the tidal range specified at the seaward boundary. Based on limited data, it appeared that the Dynamic Estuary Model was considerably more sensitive to network detail than the Thomann Model.

16. Utilizing an approach where simulated data from both tidal and nontidal models were compared, relationships of dispersion coefficients (as used in the Thomann Model) to freshwater flows were formulated for the Potomac Estuary. For the flow range investigated (930 cfs to 20,000 cfs) it was determined that dispersion coefficients (K) varied directly with flow in accordance with the following equations:

Upstream from Blue Plains

$$K = 0.195\ Q^{0.34}$$

Blue Plains to Occoquan Bay

$$K = 0.027\ Q^{0.63}$$

where:

K = dispersion coefficient ($mi^2$/day) and

Q = freshwater flow (cfs).

17. The primary disadvantage of the Thomann Model or any nontidal model is the greater significance of dispersion coefficients for an estuarine system and the need to relate them to freshwater flows, salinity gradients, and other factors.

18. Another deficiency encountered with the Thomann Model, as evidenced by certain chloride simulations and the sensitivity analysis was

the apparent deemphasis of both tidal and nontidal advective transport as a result of the model's strong dependence on dispersion. Moreover, the fact that a flow sequence is routed through the system instantaneously indicates that the hydraulic conditions influencing advection are based strictly on a velocity (Q/A) relationship and not on volume displacement.

19. Other important disadvantages of the Thomann Model are its inability to (1) branch in a lateral direction and (2) link more than two constituents.

20. Significant advantages of the Thomann Model over the FWQA Dynamic Estuary Model as both models are presently programmed are (1) its less stringent input requirements, (2) its ability through the Namelist I/O option to change input variables, such as flow on a daily basis, and thereby readily simulate interseasonal conditions, and (3) the capability of running several alternative data decks back-to-back with a minimum of effort. In short, one can generate considerably more data in much less time with the Thomann Model.

21. In addition to more demanding input requirements, another disadvantage of the Dynamic Estuary Model is the fact that it is quite costly and time consuming to link different hydraulic conditions if simulation of seasonal or annual quality characteristics is desired.

22. Because the Dynamic Estuary Model is a "real-time" system, it can predict the effect of tidal exchange and excursion on the distribution of a pollutant as well as other intratidal cycle variations in water quality and it is significantly less dependent on an empirically derived dispersion term. Other major advantages of this model are its ability to branch in a lateral direction and thereby allow simulation of water quality behavior within embayments and to consider six separate constituents either dependently or independently of one another.

# CHAPTER III

## DESCRIPTION OF THE STUDY AREA

The Potomac River Basin, draining 14,170 square miles, is the second largest watershed in the Middle Atlantic States. Its tidal portion begins at Little Falls in the Washington Metropolitan Area and extends 114 miles southeastward to the Chesapeake Bay. The section of the estuary discussed in detail in this report is the 40-mile reach extending from Key Bridge in Washington to Sandy Point which is located downstream from Quantico, Virginia (Figure I-1).

The estuary is less than 200 feet wide near its upper end at Chain Bridge and widens to approximately 4,000 yards at Sandy Point. A shipping channel with a minimum depth of 24 feet is maintained from Washington to the Chesapeake Bay. The major embayments along the upper Potomac Estuary and their surface areas are:

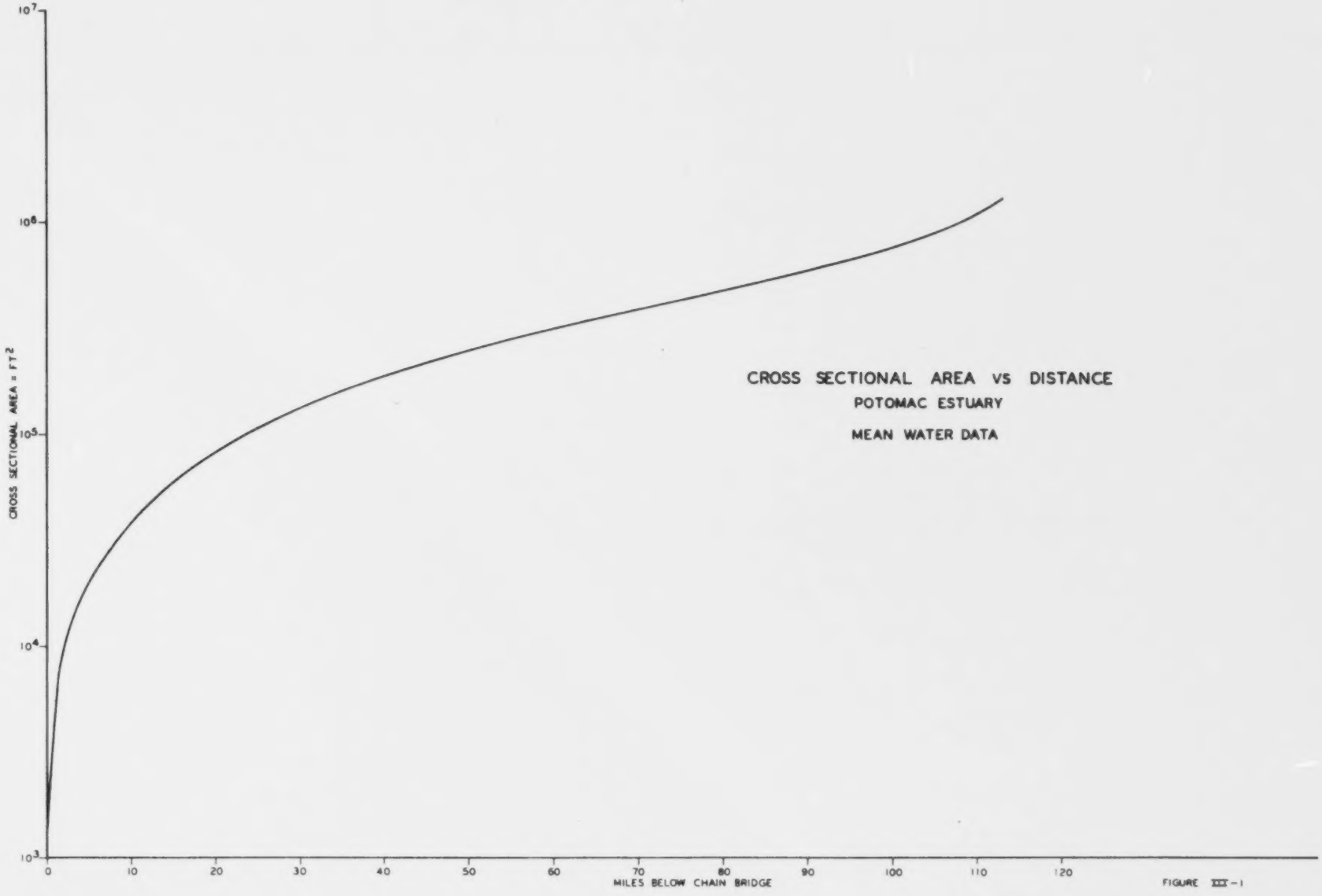
| Embayments | Surface Area |
|---|---|
| Occoquan-Belmont Bays | $218 \times 10^6$ ft$^2$ |
| Mattawoman Creek | $75 \times 10^6$ ft$^2$ |
| Gunston Cove | $65 \times 10^6$ ft$^2$ |
| Piscataway Creek | $36 \times 10^6$ ft$^2$ |
| Anacostia River | $31 \times 10^6$ ft$^2$ |
| Quantico Creek | $30 \times 10^6$ ft$^2$ |

Except for the main channel and a small reach below Chain Bridge where depths up to 80 feet occur, the estuary is relatively shallow with an average depth of about 15 feet. The embayments generally have average depths of 5 feet or less.

The upper 20 miles of the study reach (Chain Bridge to Marshall Hall) contain fresh water whereas the lower 20 miles (Marshall Hall to Sandy Point) form the transition zone from fresh to brackish water. The average tidal range at Washington is 2.9 feet, with high and low water occurring about +6 and +7 hours respectively.*

Physical data for the entire Potomac Estuary are summarized in Figure III-1 (cross-sectional area versus distance below Chain Bridge), Figure III-2 (accumulative volume versus distance below Chain Bridge), and Figure III-3 (accumulative surface area versus distance below Chain Bridge). More detailed information was recently published by CTSL in a separate report [1].

* Referenced to Piney Point (River Mile 99)




CROSS SECTIONAL AREA vs DISTANCE

POTOMAC ESTUARY

MEAN WATER DATA

FIGURE III-1

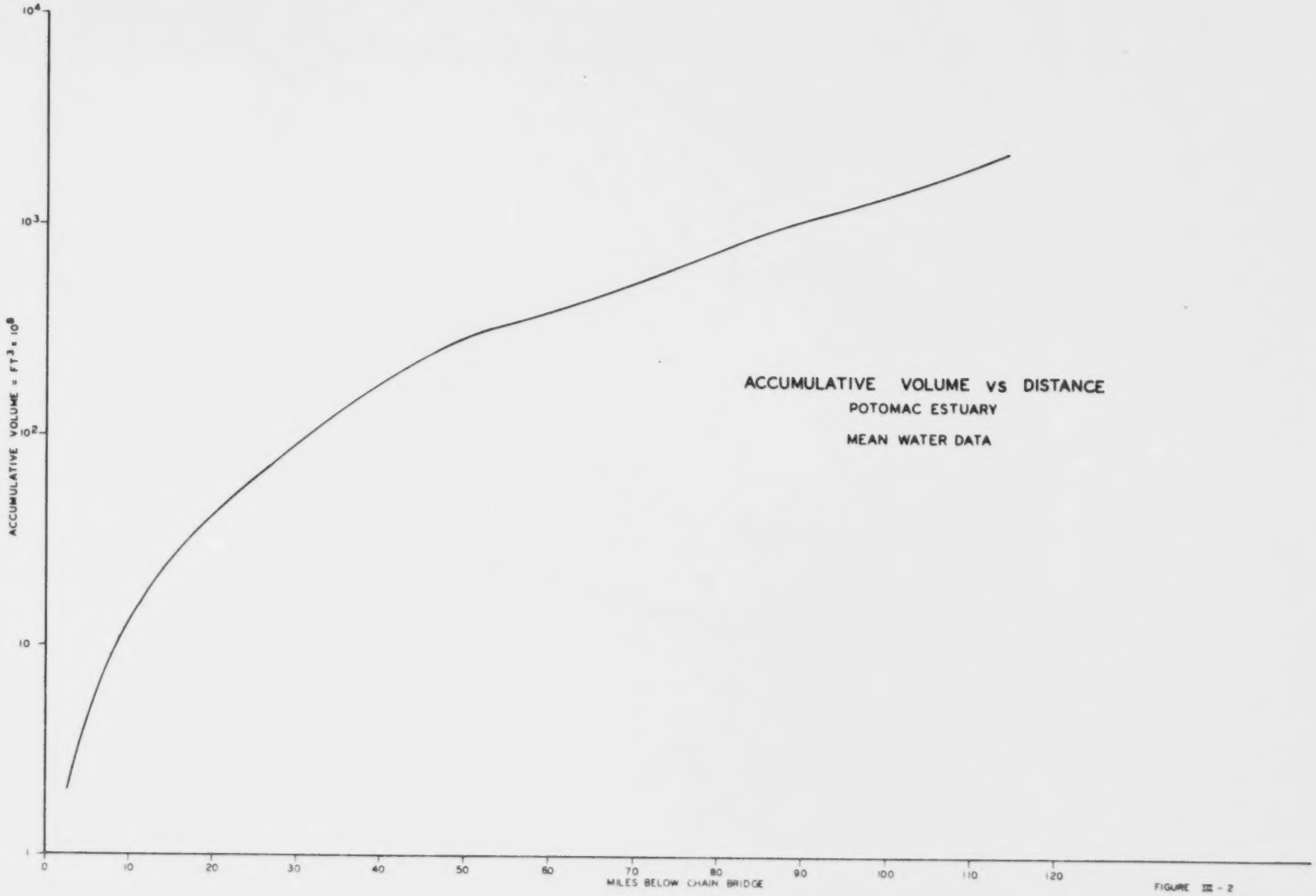

ACCUMULATIVE VOLUME = $FT^3 \times 10^8$
$10^4$
$10^3$
$10^2$
10
1
0
10
20
30
40
50
60
70
80
90
100
110
120
MILES BELOW CHAIN BRIDGE
ACCUMULATIVE VOLUME vs DISTANCE
POTOMAC ESTUARY
MEAN WATER DATA

FIGURE III - 2

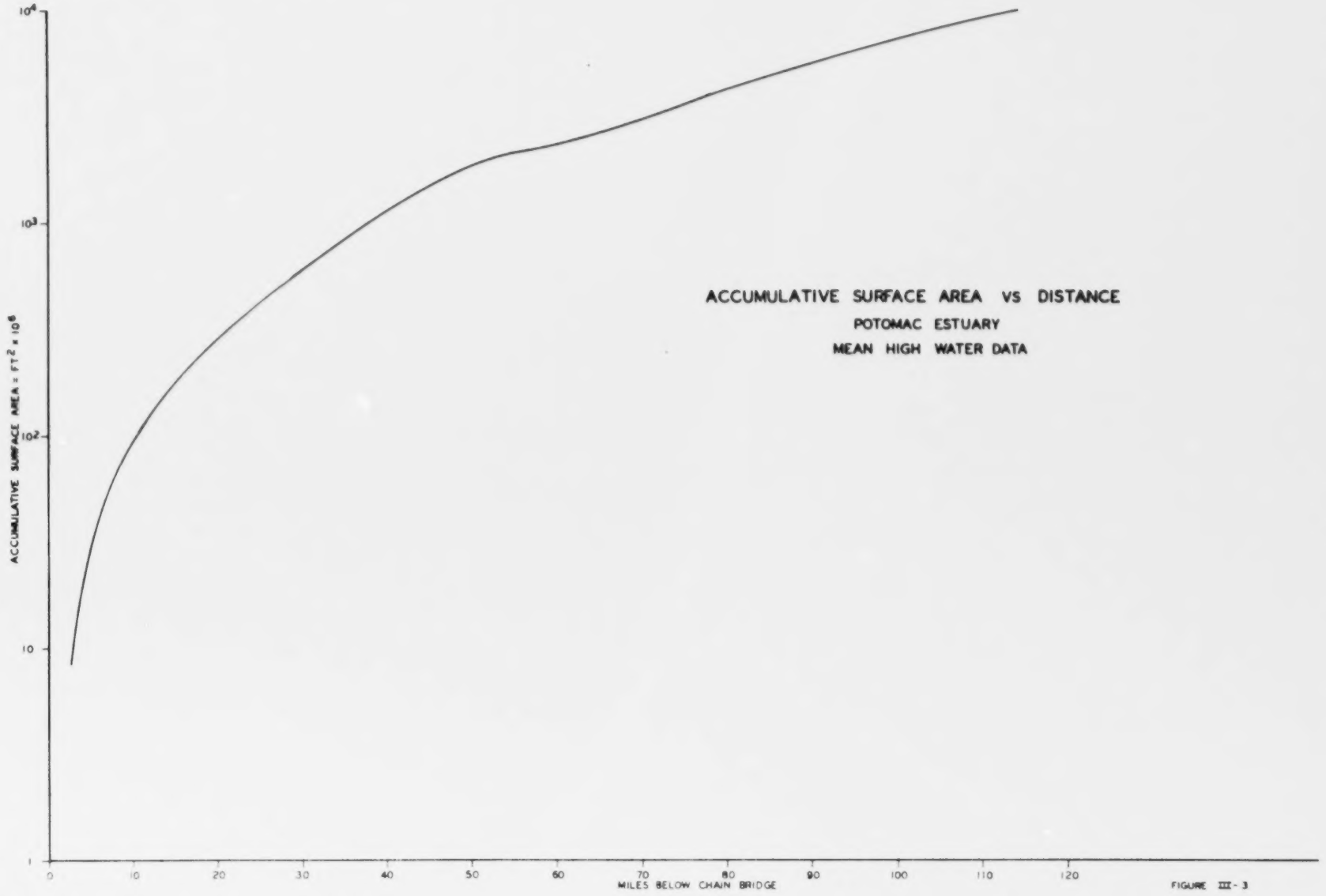

ACCUMULATIVE SURFACE AREA VS DISTANCE
POTOMAC ESTUARY
MEAN HIGH WATER DATA
ACCUMULATIVE SURFACE AREA = FT² x 10⁶
10⁴
10³
10²
10
1
0
10
20
30
40
50
60
70
80
90
100
110
120
MILES BELOW CHAIN BRIDGE

FIGURE III - 3

# CHAPTER IV

## DESCRIPTION OF MATHEMATICAL MODELS

### A. THOMANN MODEL

The Thomann Model [4] was originally developed in 1963 as a one-dimensional, steady-state, BOD-DO model specifically for the Delaware Estuary. A time-dependent version of this model [5] and a chloride model [6] were developed in 1966-1967 by General Electric under contract to the Federal Water Pollution Control Administration.* Each of the above models was applied to the Potomac Estuary shortly after development.

The time-dependent Thomann Model employs a segmented network of the water body under consideration and utilizes a finite difference approach to solve the basic mass balance equations. For the case of BOD and DO, these equations can be written as follows:

$$\square B \square \, [L_i] + \left[\frac{dL}{dt_i}\right] = [J_i]$$

$$\square A \square \, [c_i] + \left[\frac{dc}{dt_i}\right] = [r_i \, c_{s_i} + P_i - d_i \, L_i]$$

where $\square \; \square$ denotes a square matrix of order n and [ ] denotes a column vector of dimension n (n is equal to the number of segments in the system).

The total number of equations and unknowns equals 2n. The components of matrices A and B are defined as:

$$A_{i,\,i-1} = B_{i,\,i-1} = \frac{\alpha_i \, Q_j + E_i}{V_i}$$

$$A_{i,\,i} = \frac{(\phi_i - \alpha_{i+1}) \, Q_j - E_i - E_{i+1}}{V_i} - r_j$$

* Now Environmental Protection Agency

$$B_{i,\,i} = \frac{(\phi_i - \alpha_{i+1})\,Q_j - E_i - E_{i+1}}{V_i} - d_j$$

$$A_{i,\,i+1} = B_{i,\,i+1} = \frac{E_{i+1} - \phi_{i+1}\,Q_j}{V_i}$$

The remainder of the terms are defined below:

$L$ = BOD

$C$ = DO

$J_i$ = forcing function or loading in section i

$r_j$ = reaeration coefficient

$C_s$ = saturation value of DO

$d_j$ = decay coefficient

$P_i$ = other sources and sinks of oxygen

$V_i$ = volume of segment i

$Q_j$ = net flow

$E_i$ = eddy exchange coefficient

$\alpha_{i\,j}$, $\phi_i$ = advection factors

Of special importance are the eddy exchange coefficient and the advection factors. The eddy exchange coefficient is used to describe the tidal and other nonadvective effects on the transport of a constituent. Between sections i and i + 1, it can be computed as follows:

$$E_{i,\,j} = \frac{K_{i,\,j} \times A_{i,\,j}}{\frac{1}{2}(L_i + L_{i+1})} \times 27.878 \times 10^6$$

where:

$K_{i,j}$ = eddy diffusion coefficient between sections i and i + 1 ($mi^2$/day)

$A_{i,j}$ = cross-sectional area at the boundary of segments i and i + 1, and

$L_i$ = length of segment i

The purpose of the advection factor is to serve as a means of computing the concentration of a constituent at the interface of two segments by "weighing" the concentrations in these two adjacent segments. In order to guarantee positivity in the solution, the advection factor takes on the following definition:

$$\phi_{i,j} = \frac{1}{2}\left(\frac{E_{i-1,j}}{Q_{i-1,j}} + \frac{E_{i,j}}{Q_{i,j}}\right)$$

$$\text{if } \frac{E_{i-1,j}}{Q_{i-1,j}} > \frac{E_{i,j}}{Q_{i,j}} \text{ then } \phi_{i,j} = \frac{E_{i,j}}{Q_{i,j}}$$

$$\text{if } \phi_{i,j} > 0.5 \text{ then } \phi_{i,j} = 0.5$$

for the first section:

$$\frac{E_{o,j}}{Q_{o,j}} = 0.0$$

in which case $\alpha$ = 1.0 (pure advection). If the concentrations in the adjoining sections are to be weighed equally (pure dispersion both $\phi$ and $\alpha$ are 0.5.

The simultaneous, linear, first-order differential equations employed by the Thomann Model express the time rate of change of pollutant concentration as a function of the advection and dispersion components at each segment interface and sources and sinks within each segment. These equations are numerically integrated by a fourth-order Runge-Kutta procedure whereby the truncation error is kept within some preset allowable value by constant adjustment of the time step size. The solution yields a mean tide concentation of a particular constituent for every segment.

Since the Thomann Model does not have a "real-time" solution where tidal movement is explicitly considered in the mass transfer equations, the dispersion coefficient (K) must be an "all-inclusive" term that can grossly represent tidal behavior. Another source of uncertainty is numerical dispersion which is introduced by the assumption of a completely mixed finite volume.

B. FWQA DYNAMIC ESTUARY MODEL

The DEM represents the two-dimensional flow and mass transfer within an estuary by a network of interconnecting junctions and channels. Uniformity must be assumed only in the vertical direction. The hydraulic component of the model essentially solves the equations describing the propagation of a long wave (tidal) through a shallow water system. When the tidal conditions such as amplitude, period, etc. existing at the seaward boundary are known, this solution can be obtained from the one-dimensional form of the equations of motion and continuity. The equation of motion is:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - K/u/u - g\frac{\partial H}{\partial x}$$

where:

u = velocity along x axis

x = distance along x axis

H = water surface elevation

g = acceleration of gravity

K = frictional resistance coefficient

t = time

The equation of continuity can be expressed as:

$$\frac{\partial H}{\partial t} = -\frac{1}{b}\frac{\partial (uA)}{\partial x}$$

where:

b = mean channel width

A = cross-sectional area of the channel

The equation of motion is applied to the channel elements to predict velocity and flow and the continuity equation is associated with the junctions and accounts for tidal fluctuations in the water surface elevation (head) and corresponding changes in volume. Both of these differential equations are converted to finite difference form and solved by numerical integration techniques (predictor-corrector method) to yield a "real-time" hydraulic solution. The time step used is normally very small, i.e., 1-5 minutes, as dictated by the network and by numerical stability. The solution will converge for a given set of boundary conditions (including tides and freshwater flow rates) to a dynamic equilibrium having velocities, flows, and heads repeated at intervals equal to the specified tidal period.

The quality component of the FWQA model incorporates the two basic transport mechanisms; namely, advection and diffusion, and requires the dynamic steady-state hydraulic solution as input. Advective transport is primarily a hydraulic mechanism that moves the constituent in the direction of flow. It can be represented by the following two equations:

$$\frac{\partial c}{\partial t} = U \frac{\partial c}{\partial x}$$

or in terms of mass and in finite difference form

$$\frac{\Delta M}{\Delta t} = A\ U\ c^*$$

where:

$c^*$ = concentration in advected water

$U$ = channel velocity, and

$A$ = channel area

The determination of c* can present special problems such as computational instability and "numerical mixing." Previous studies have indicated that an advected concentration equal to that at one-quarter of the channel length, measured in the direction of decreasing gradient, generally proved satisfactory.

Diffusion (eddy) is represented in the model as a physical-chemical transport mechanism dependent only upon concentration gradients. Mathematically, it can be expressed as:

$$\frac{\partial c}{\partial t} = K \frac{\partial^2 c}{\partial x^2}$$

or again in terms of mass

$$\frac{\Delta M}{\Delta t} = KA \frac{\Delta c}{x}$$

where:

$\Delta c$ = concentration gradient within a channel

$x$ = channel length, and

$K$ = diffusion coefficient

The diffusion coefficient has a dimension of length squared over time and can be defined by the following equation:

$$K = C_4/U/R$$

where:

$C_4$ = a constant

$U$ = mean channel velocity, and

$R$ = hydraulic radius of channel.

As currently programmed, a maximum of six constituents can be handled simultaneously in the FWQA model. They may be either conservative or nonconservative and may be interrelated in any mathematically describable fashion. Recent modifications have enabled this model to quantitatively consider terms other than carbonaceous BOD oxidation and reaeration in the DO budget. For example, nitrification, benthic oxygen demand, and phytoplankton photosynthesis and respiration have also been included.

The model will compute constituent concentrations throughout the system by means of a numerical integration solution of the above finite difference equations describing advection and diffusion as well as those expressing degradation and the constituent's other sources and sinks. While maintaining mass continuity, the solution proceeds from channel to channel and junction to junction performing the appropriate transfers over a specified time step.

In order to minimize "induced dispersion" or numerical mixing, ample consideration should be given to the network layout and to selection of the time step. Ideally, the ratio of fluid displacement ($U\Delta t$) to the channel length ($x$) should approach unity.

# CHAPTER V

## MATHEMATICAL MODEL SIMULATIONS OF 1969-1970 DYE RELEASES

### A. THOMANN MODEL

#### 1. Simulations and Verification

##### a. Potomac Dye Study

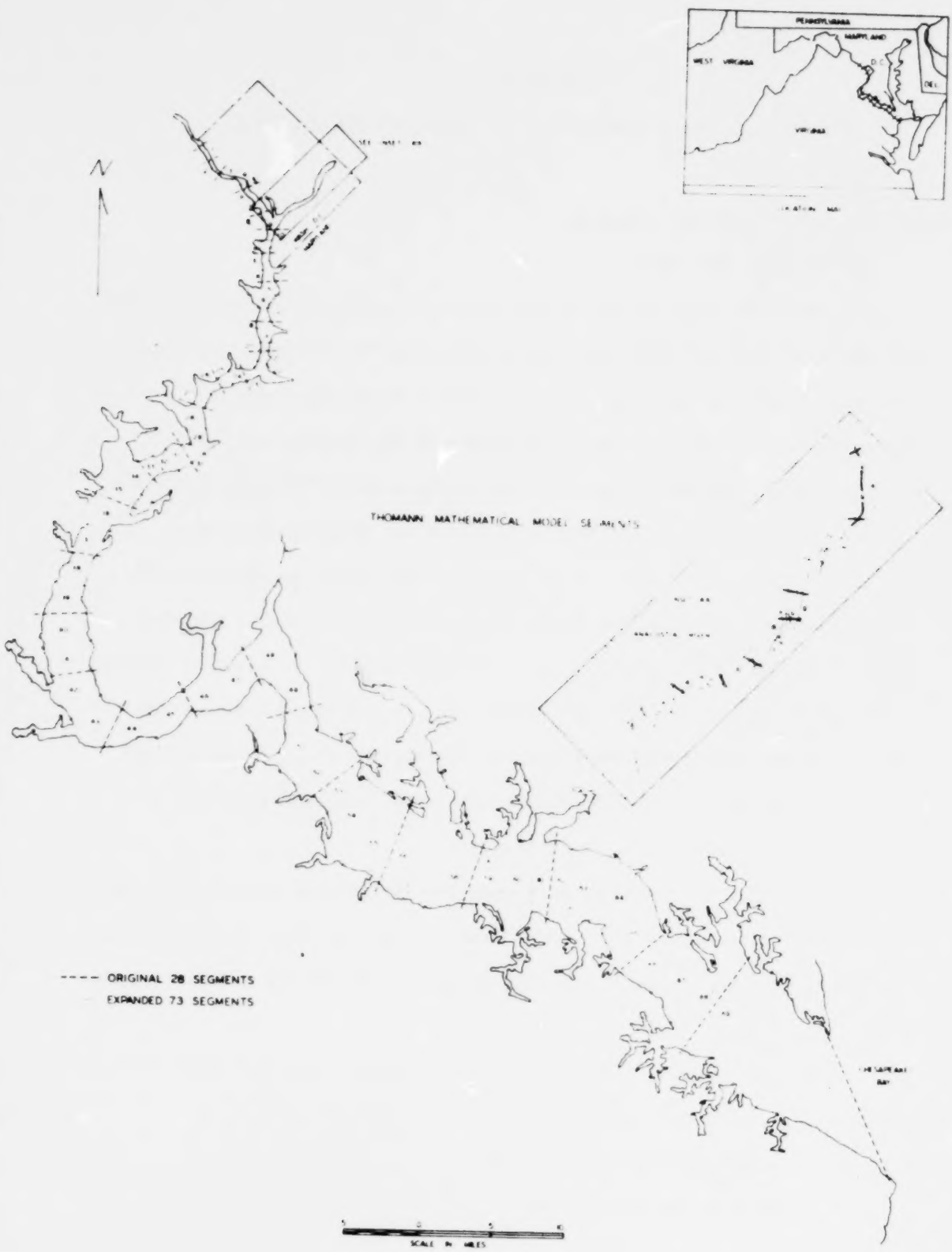
It should be noted at the outset that all mathematical model verifications involving the 1969 dye release data were based upon a dye loss rate of 0.03 per day as computed in Section A-3c of the Appendix. While other values for loss rate were considered in the Thomann and Dynamic Estuary models, the most favorable output was obtained with the 0.03 per day rate. Moreover,since neither background nor boundary data were collected prior to this dye study, the upper and lower boundary concentrations as well as a uniform background concentration of 0.1 ppb were arbitrarily specified in both models to compensate for differences between observed and discharged dye quantities. An evaluation of the sampling data collected from areas where dye was nonexistent and from background data collected during the 1965 Potomac dye study provided some insight into the magnitude of these concentrations.

The expanded segmented network used for the Potomac Estuary Thomann Model is shown in Figure V-1. Model simulations discussed in this section were made using the upper 35 segments between Chain Bridge and Mattawoman Creek.

During the simulation and verification studies, special consideration was given to the following:

1) Advection factors ($\phi$, $\alpha$), and

2) Dispersion coefficient (K).




# POTOMAC ESTUARY

FIGURE V-1

As described previously, the advective proportionality factors are used to determine the constituent concentration at a segment interface as a function of the concentrations in the adjoining segments. This concentration, when multiplied by a net flow across the interface, yields the quantity of constituent advected from one segment to another. Theoretically, $\alpha$ must range between 1.0 (nontidal or pure advection system) and 0.5 (pure tidal system with no net advective flow). In the original Thomann time-dependent model, $\phi$ was computed from the ratio E/Q, where E is the eddy exchange coefficient ($ft^3/day$) and Q is net flow and $\alpha$ was equal to $1 - \phi$. Since there was no stipulation on the magnitude of $\alpha$, a program modification was made to maintain its value between these specified limits. A sensitivity analysis of $\alpha$ on model predictions is presented in Chapter VI.

The major problem involved with verifying the Thomann Model was estimating the longitudinal dispersion coefficient (K). This is a complex parameter affected by (1) freshwater inflow rates, (2) salinity gradients, (3) estuary geometry, and (4) tidal conditions.

The relationship between freshwater flow rates and dispersion coefficients is presented in Chapter VI. Salinity has a very pronounced effect on dispersion due to density gradients causing significant changes in the boundary shear velocity distribution. As reported by Harleman [7], dispersion coefficients calculated for freshwater and high salinity areas in a constant area estuary (Rotterdam Waterway) were 0.5 $mi^2/day$ and 40 $mi^2/day$ respectively.

The geometry of the channel and the tidal conditions also affect the extent of dispersion although quantitative relationships among the three have not been determined in this report. A sensitivity analysis of the dispersion coefficient in the Thomann Model is presented in Chapter VI.

In an attempt to verify the Thomann Model, several runs were made using the 1969 dye release data, each with different dispersion coefficients. The most favorable agreement between observed and simulated spatial profiles was noted utilizing the coefficients shown below:

| Segment Numbers | Time Period | |
|---|---|---|
| | November 1-5 | November 6-30 |
| 1 - 13 (upstream of discharge) | K = 2.0 | K = 3.0* |
| 14 - 37 (downstream of discharge) | K = 3.0 | K = 5.0* |

* Dispersion coefficients were increased after November 5, to reflect the increased freshwater inflows and were increased farther downstream to reflect geometry and salinity changes.

The simulated spatial profiles obtained from the Thomann time-dependent model and the observed profiles at high- and low-slack tide are shown in Figures V-2 through V-6 for 5 different days of the study period. Major emphasis during model verification studies was placed upon closely simulating dye peaks, both spatially and in magnitude, and achieving similarly shaped curves. It was also important that simulated profiles generally fall within high- and low-slack water observed data since they do represent mean tide conditions. As can be seen in these figures, acceptable agreement between prototype and model data was

generally obtained but certain discrepancies did arise. The primary shortcoming in the Thomann Model simulations appeared to be the pronounced "peaking" that occurred during the early period of the study. The simulated profiles for November 6 (Figure V-2), November 7 (Figure V-3), and November 10 (Figure V-4) show extremely sharp and somewhat greater peaks as compared to prototype data. Another difficulty encountered with some of the Thomann Model simulations was insufficient downstream movement of peak concentrations. This is evident in Figures V-3, V-5, and V-6.

A refinement in the estuary segmentation did not resolve the above problems. Increasing the dispersion coefficient lowered the peaks but the configuration of the curve was adversely affected for model verification. It appeared that all of the problems associated with simulation of dye peaks were created by the nontidal approach or the analytical mathematical solution of the basic equations employed by the Thomann Model.

A station history or temporal verification of the dye release data with the Thomann Model simulations discussed previously is shown for four selected sampling stations in Figure V-7.

THOMANN MODEL DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 6, 1969

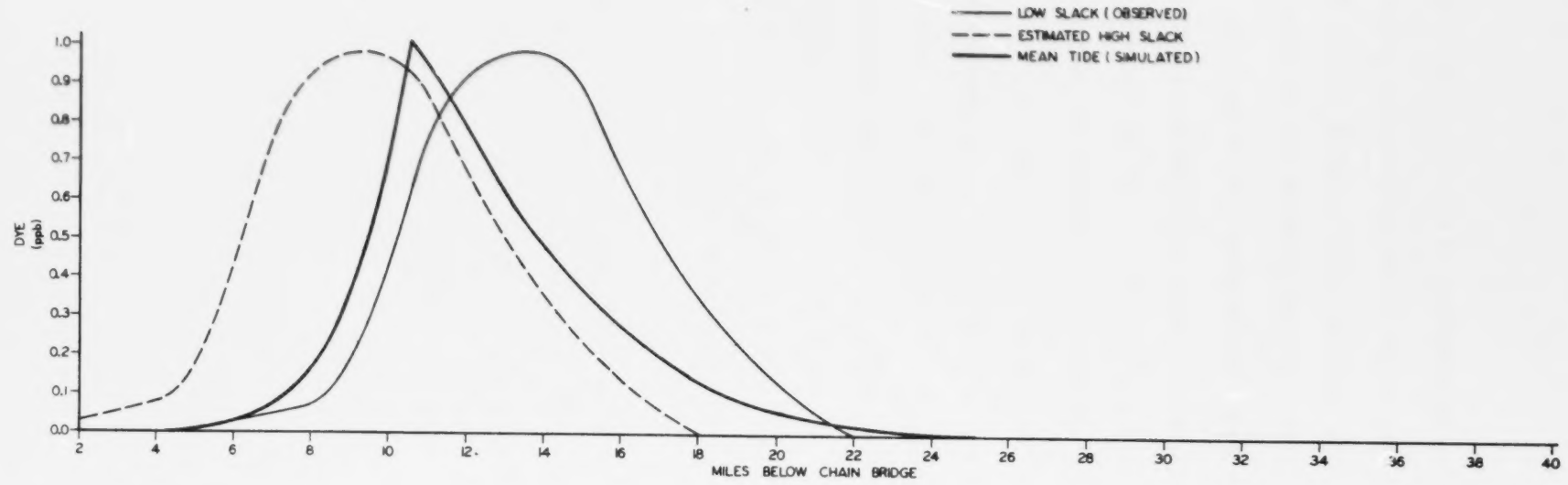



FIGURE II-2

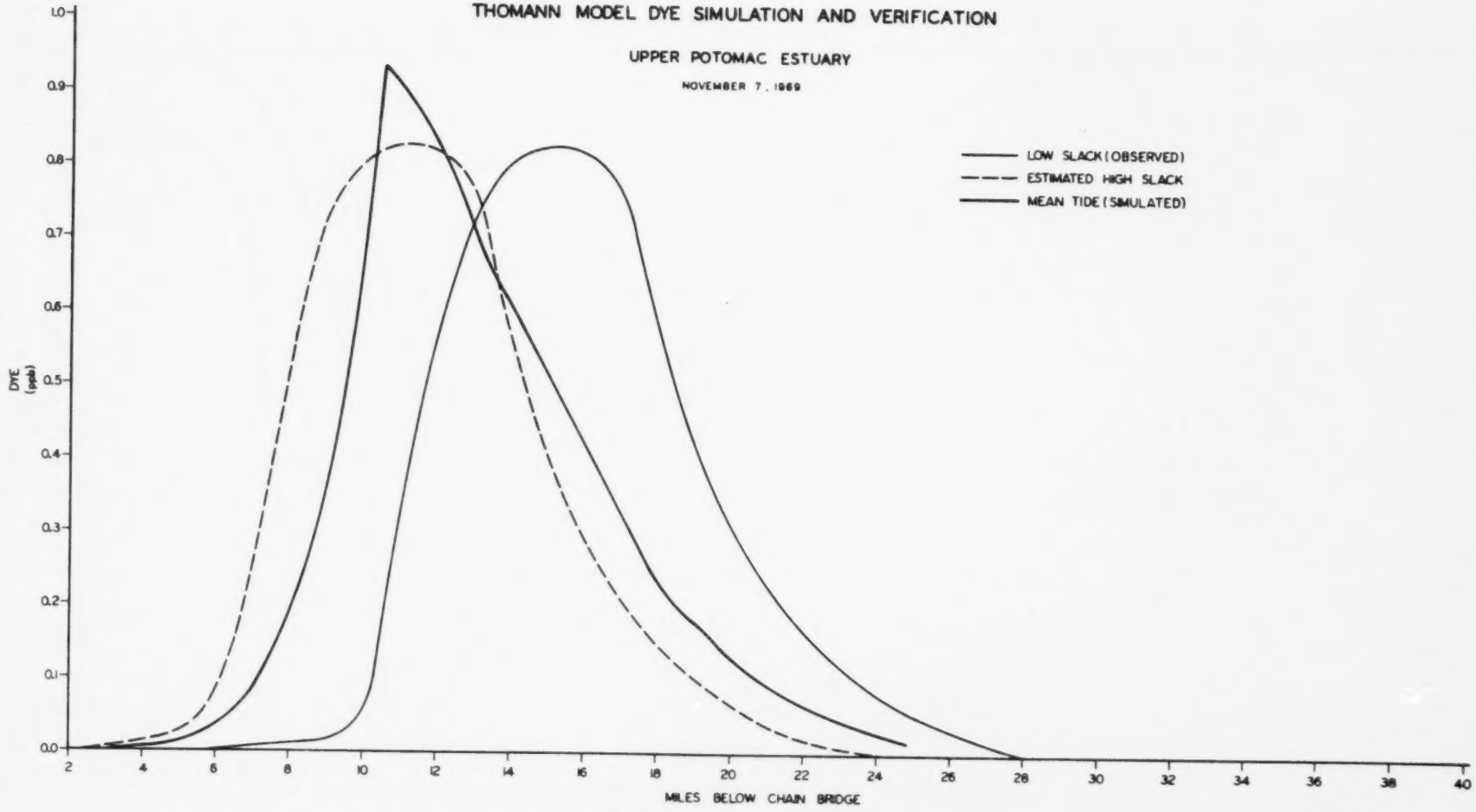

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 7, 1969
LOW SLACK (OBSERVED)
ESTIMATED HIGH SLACK
MEAN TIDE (SIMULATED)
DYE (ppb)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE II-3

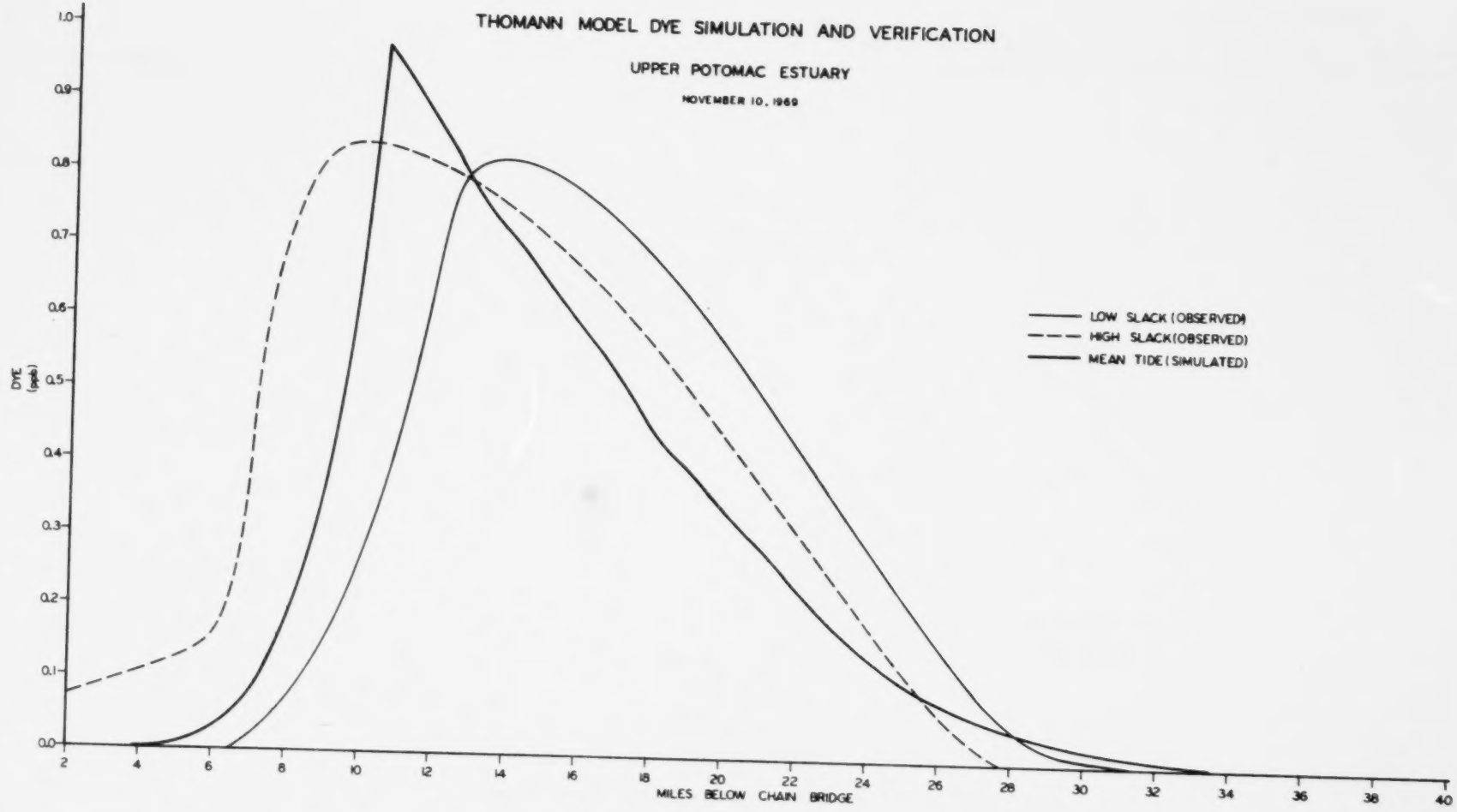

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 10, 1969
DYE (ppb)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE
LOW SLACK (OBSERVED)
HIGH SLACK (OBSERVED)
MEAN TIDE (SIMULATED)

FIGURE III-4

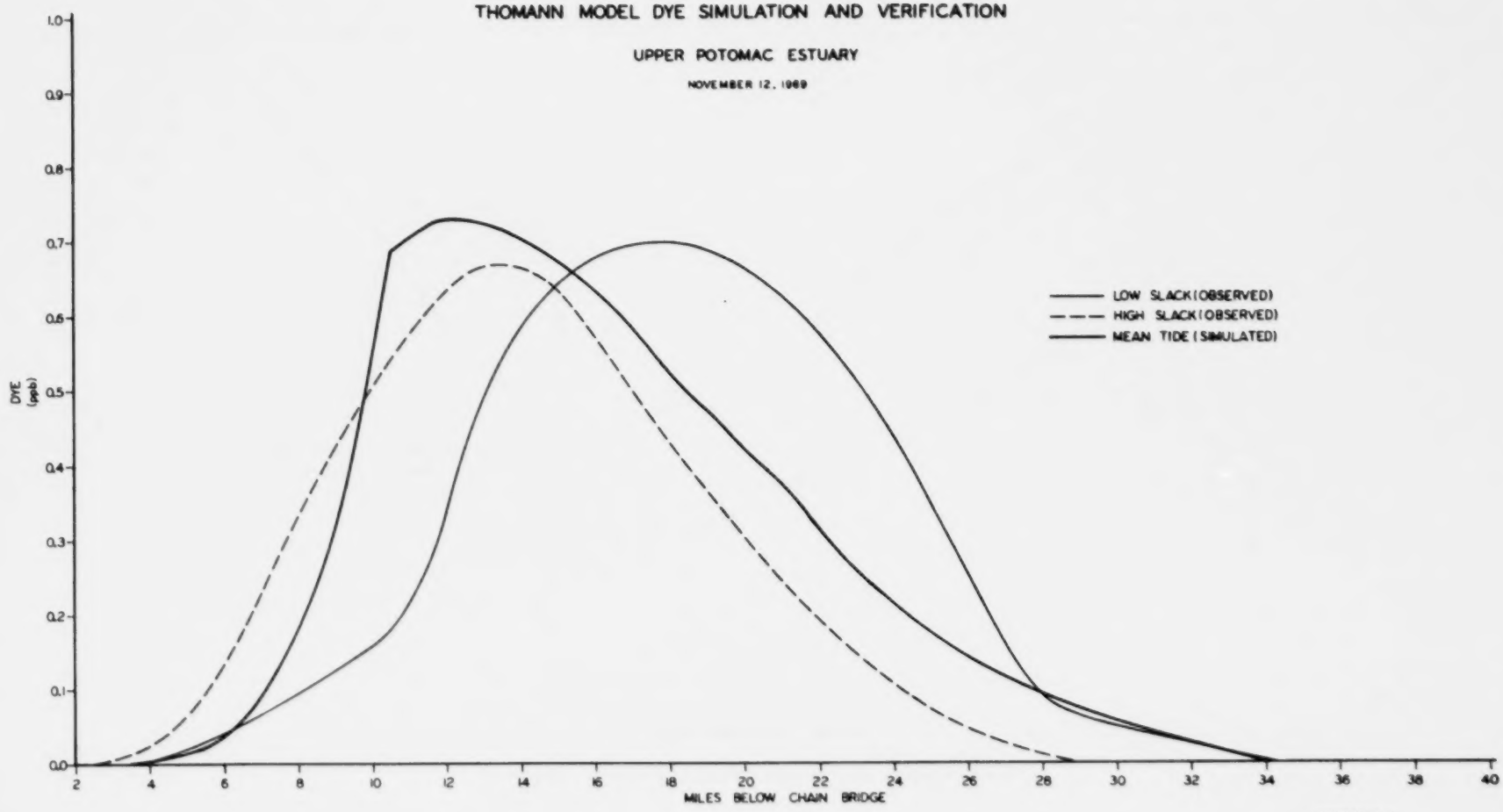

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 12, 1969
DYE (ppb)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE
LOW SLACK (OBSERVED)
HIGH SLACK (OBSERVED)
MEAN TIDE (SIMULATED)

FIGURE II-5

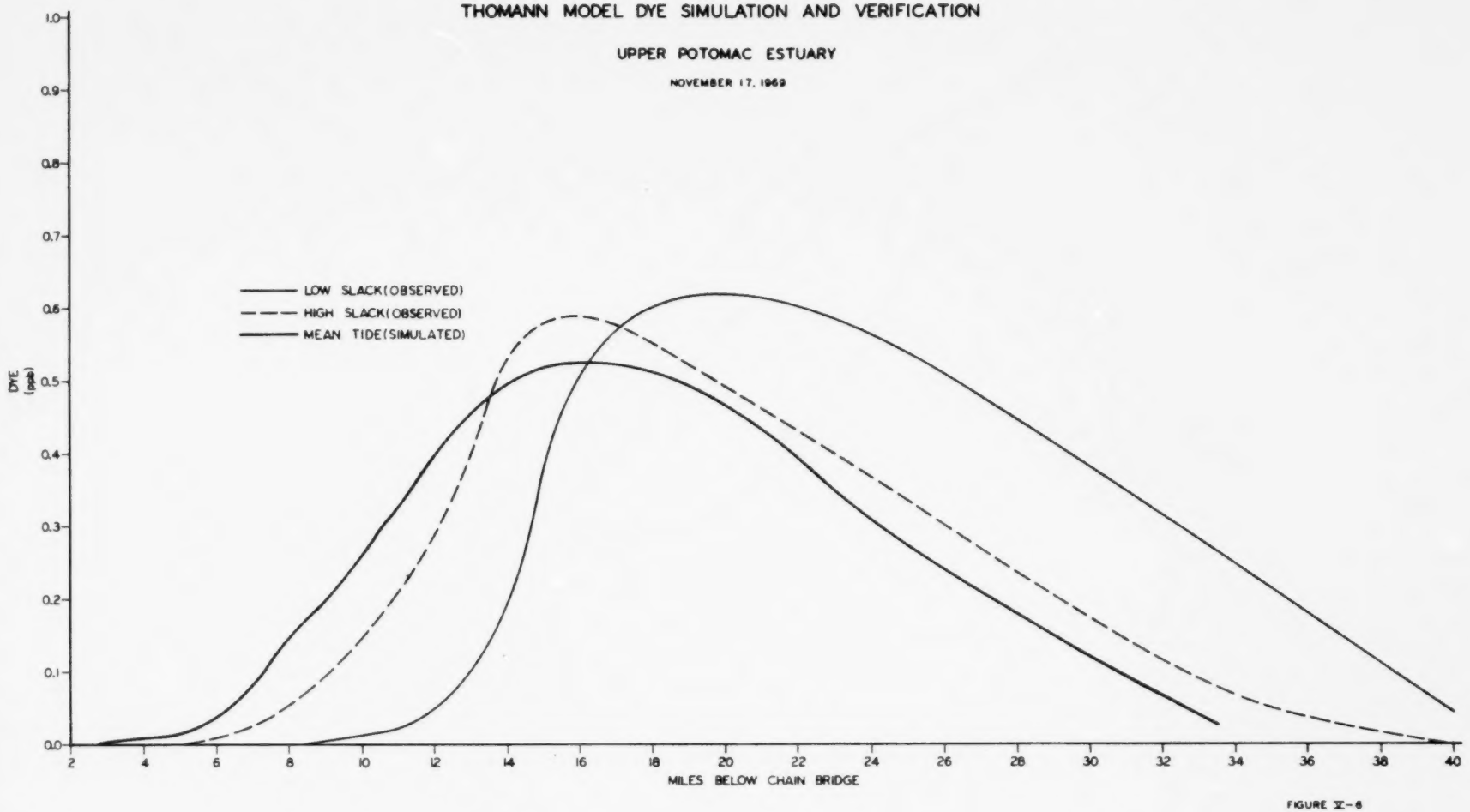

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 17, 1969
LOW SLACK(OBSERVED)
HIGH SLACK(OBSERVED)
MEAN TIDE(SIMULATED)
DYE (ppb)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE II-6

# TEMPORAL DYE PROFILES

## UPPER POTOMAC ESTUARY

THOMANN MODEL

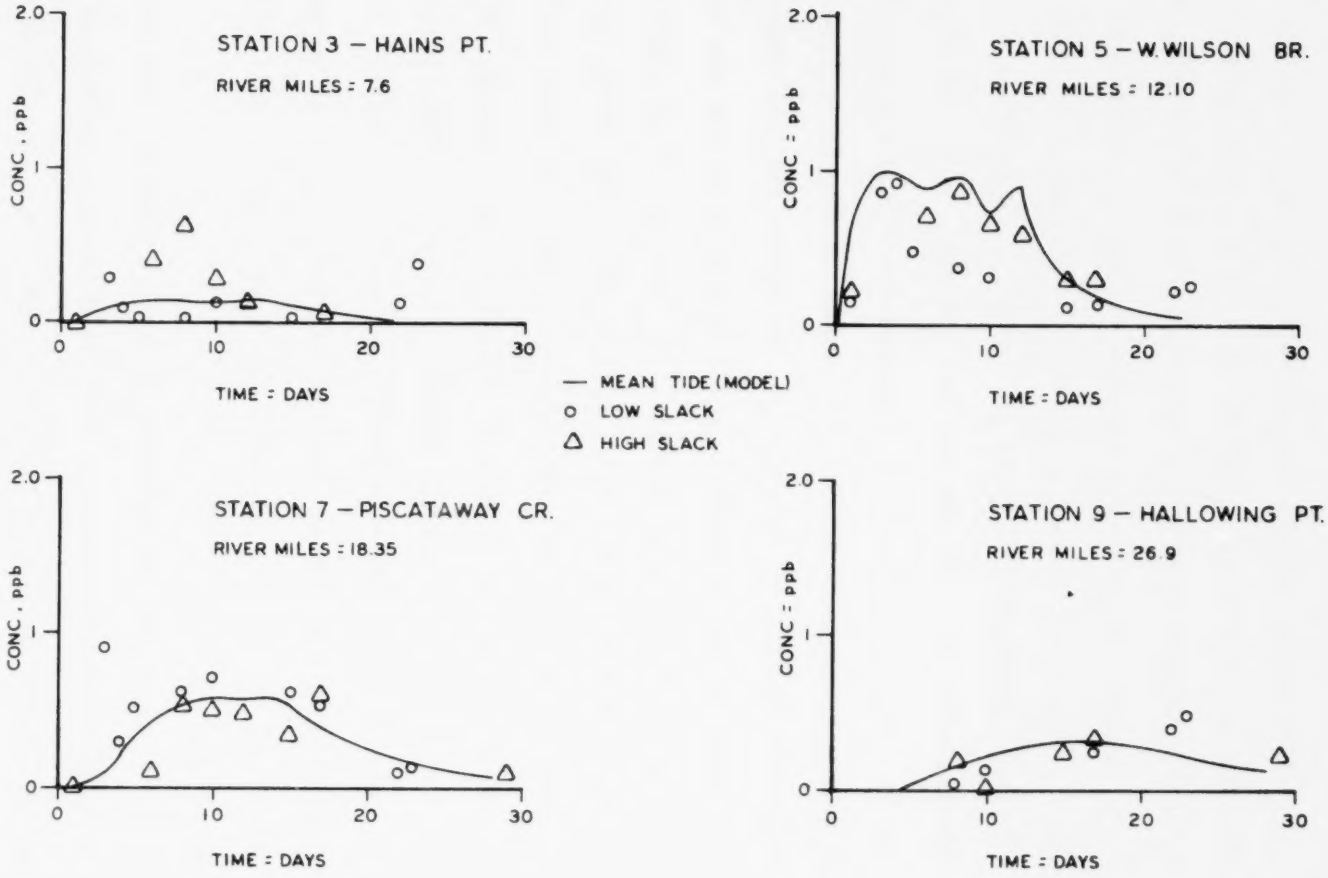



FIGURE V-7

b. Anacostia Dye Study

The segmented network applied to the Anacostia tidal system for modeling purposes is presented in Figure V-1. The problem of verifying the Thomann Model based upon 1970 Anacostia dye study data was again essentially one of evaluating a dispersion coefficient to yield the best agreement between observed and simulated data. The dye loss rate was specified as 0.05 per day for all simulation runs. After several trial runs, it appeared that a K value of 0.7 $mi^2$/day produced the most satisfactory results. Attempting to vary the dispersion coefficient longitudinally or relating it to freshwater flow, as was done with the Potomac, did not seem to improve the simulated data.

Observed spatial profiles and simulated data from the Thomann Model are shown in Figures V-8 through V-12. An analysis of these figures indicates that the basic configurations of the two curves are generally similar for various times in the study, especially those portions representing the leading edge of the dye cloud. Moreover, relatively close agreement was obtained between observed and simulated peak dye concentrations insofar as magnitude was concerned. Again, a major shortcoming of the Thomann Model predictions, which can be seen in several of the figures, was an insufficient rate of longitudinal peak movement.

The net advective transport of the dye cloud's centroid was not accurately simulated with the range of dispersion coefficients investigated. As was noted with the Potomac dye study, the effects of such factors as extreme and "flashy" flow variation and unusually high or

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

APRIL 23, 1970

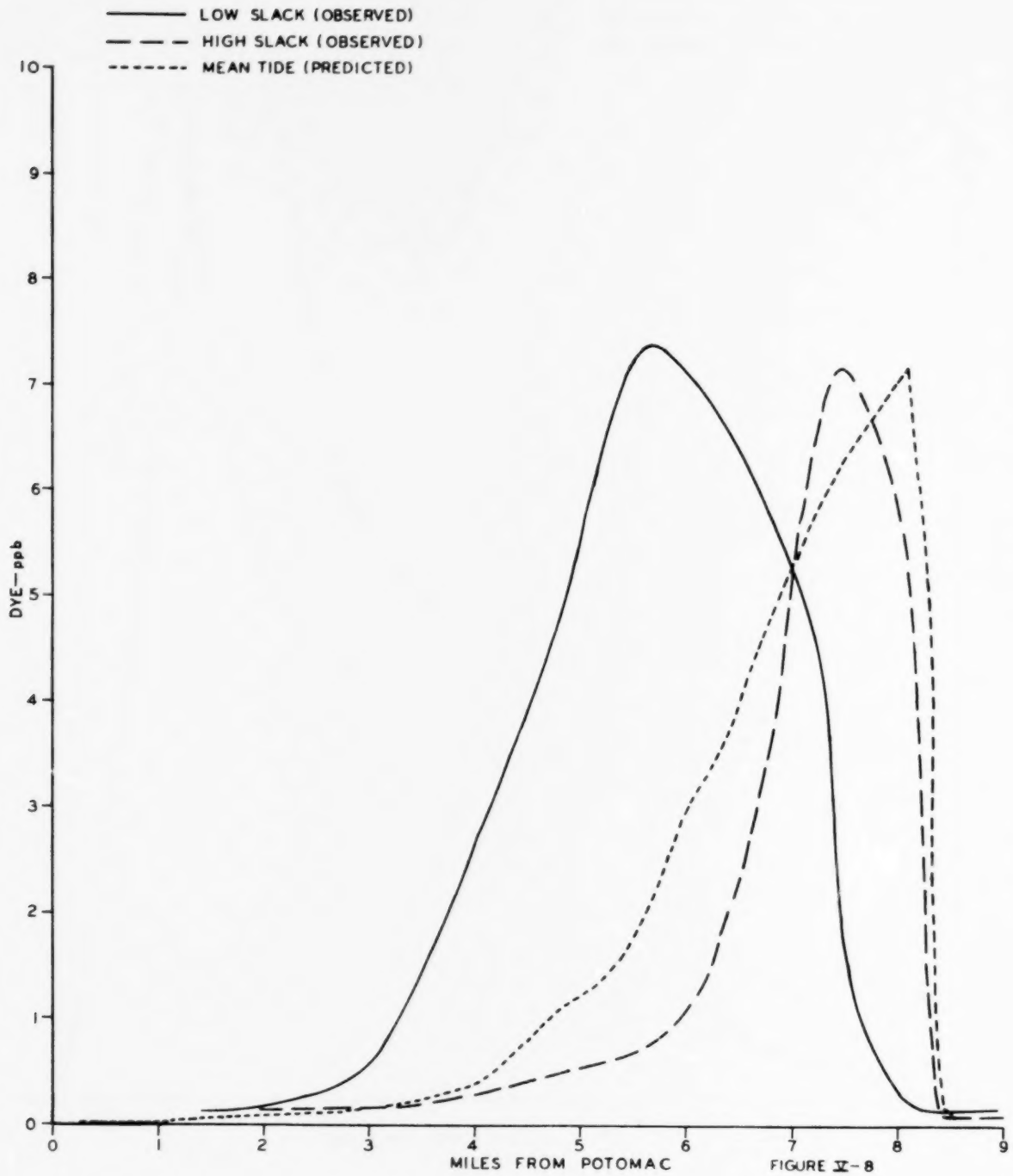



FIGURE V-8

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

APRIL 27, 1970

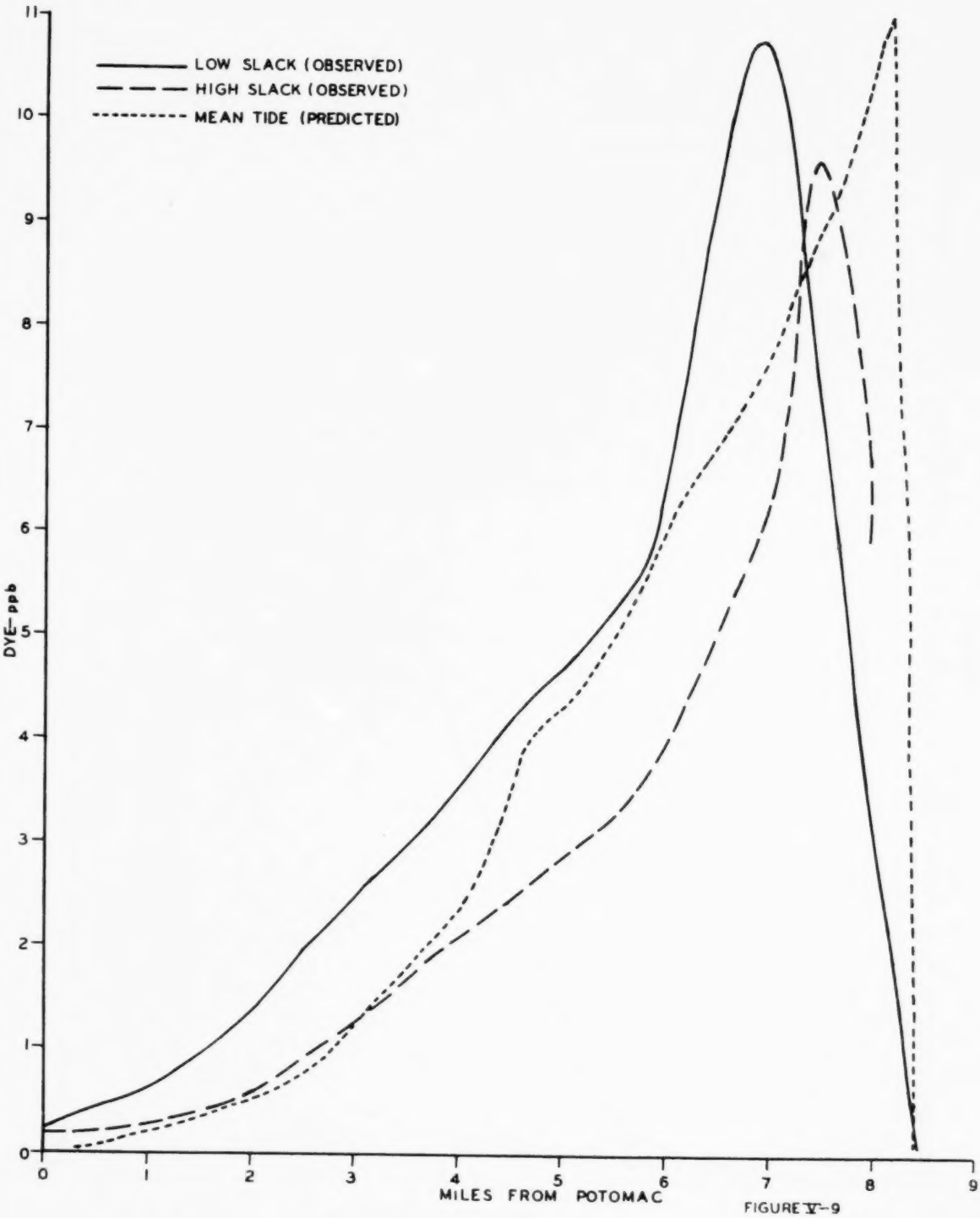



FIGURE V-9

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

APRIL 29, 1970

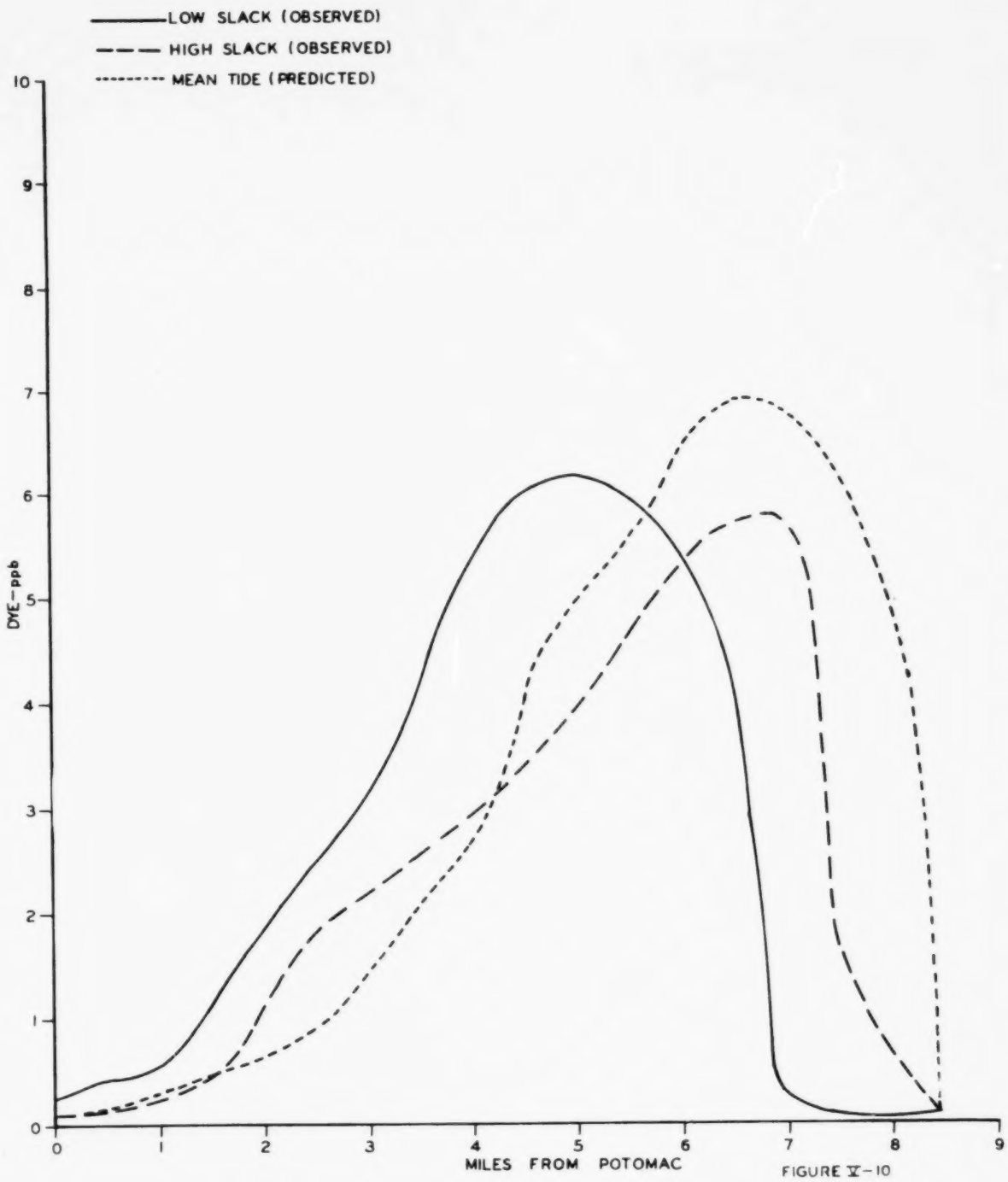



FIGURE V-10

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

MAY 4, 1970

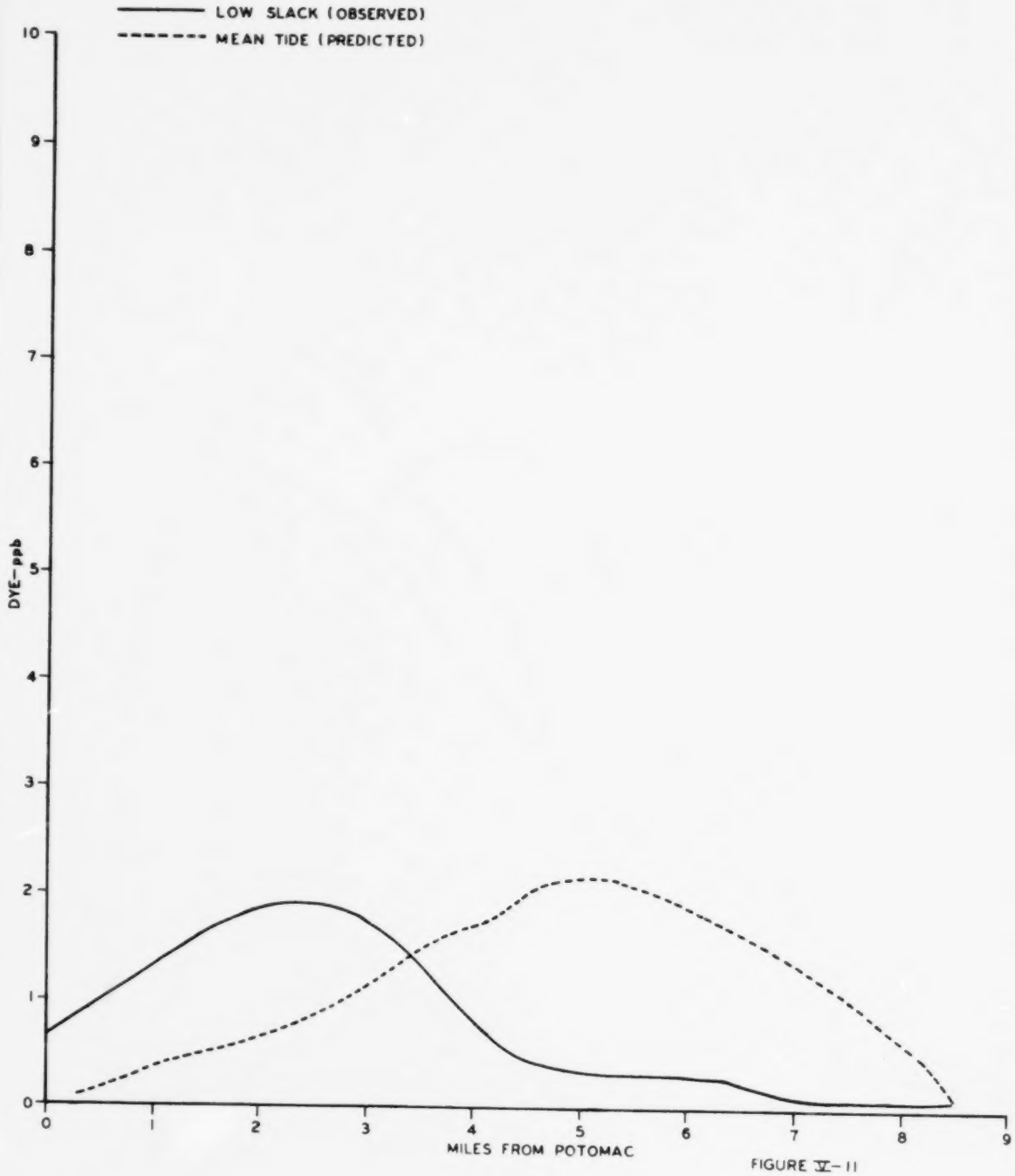



FIGURE V-11

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

MAY 7, 1970

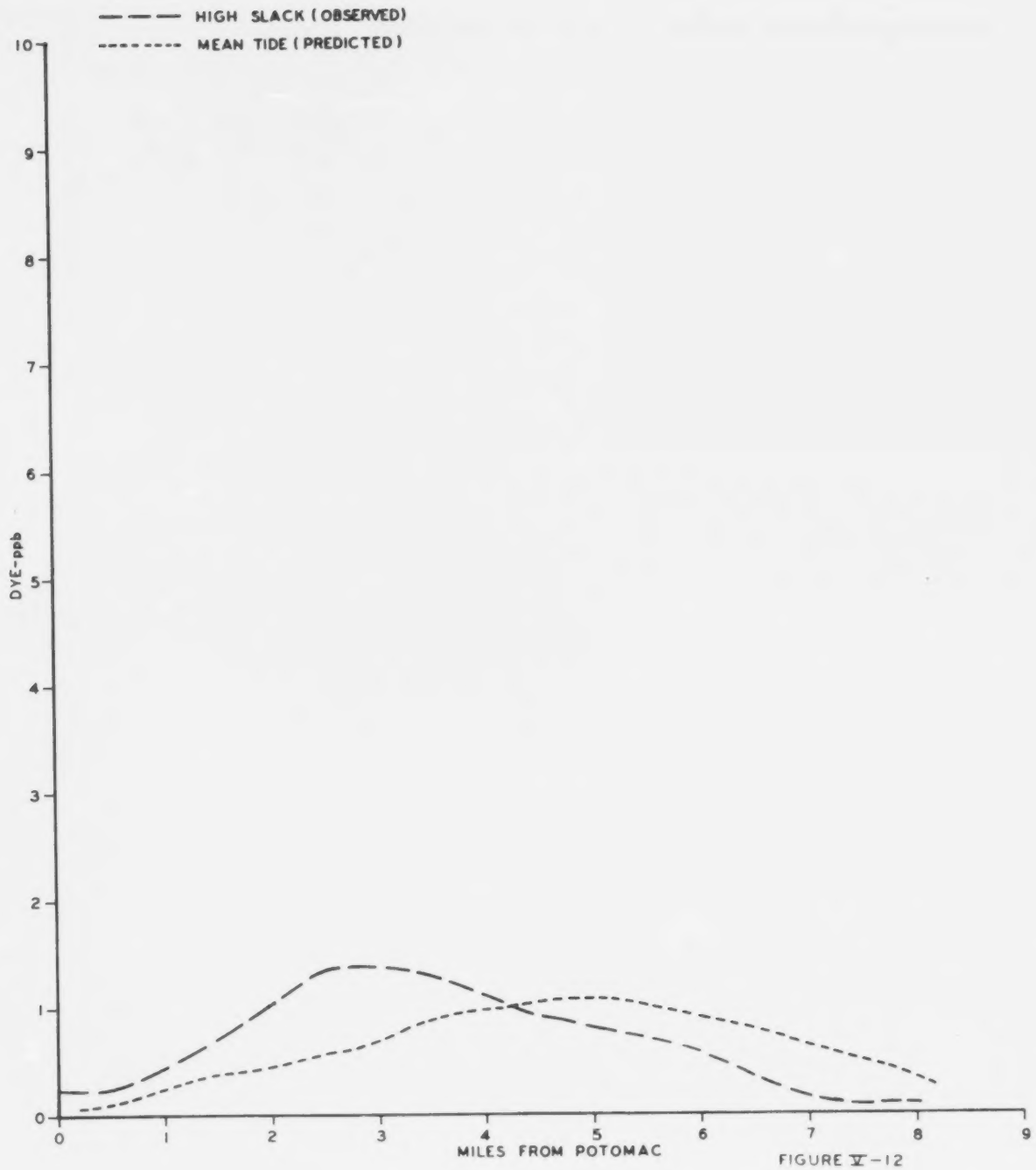



FIGURE V-12

low tides with the corresponding changes in tidal excursion and advection which generally accompany a long-term study are not adequately incorporated in the nontidal model and while the dispersion coefficient does exert considerable influence, there are limitations present.

B. FWQA's DYNAMIC ESTUARY MODEL

1. Simulations and Verification

a. Potomac Dye Study

The network of junctions comprising the Dynamic Estuary Model for the main Potomac are basically the same as those shown in Figure V-1. The simulation data presented herein pertain to the 35 junctions upstream from Occoquan Bay.

The verification of the Dynamic Estuary Model based upon 1969 dye study data initially required a reliable representation of the hydrodynamics during the study period. For sake of convenience, only two hydraulic conditions were simulated. The period from November 1-5 assumed an average flow of 1,886 cfs. The remainder of November was assigned an average flow of 3,974 cfs. The actual tidal record at Piney Point, Maryland, (near the seaward boundary) was obtained from the U. S. Coast and Geodetic Survey for the month of November. A somewhat typical tide, having a period of 12.5 hours, was selected and assumed to recur continuously throughout the study period. Hydraulic runs using different Manning coefficients were tried until the simulated tidal data at Washington, including ranges and phasing, compared favorably with corresponding observed data. Predicted tidal data at intermediate stations throughout the estuary were also compared with observed data for hydraulic verification.

Insofar as the quality program is concerned, consideration was given to (1) appropriate dye loading rate, and (2) dispersion term $C_4$*. Since dye loading rates were computed for each 4-hour interval of the 13-day release period, a similar procedure was used in the model. Simulations were based on varying the dye concentrations in the effluent every 4 hours until the 13th day when the dye release was shut off entirely. While the dispersion coefficient is relatively unimportant in this model as compared to the Thomann Model, the initial value of 2.5 used for $C_4$ was considered too low and was subsequently increased an order of magnitude to 25. For a tidal velocity of 1.5 ft/sec and a channel depth of 15 feet, a $C_4$ of 25.0 would translate to a dispersion coefficient of 1.7 $mi^2$/day. This value yielded better results and additional refinement in the dispersion coefficient did not appear warranted.

The simulated dye profiles obtained from the Dynamic Estuary Model for the conditions and assumptions described above are shown in Figures V-13 through V-16. Also shown are high- and low-slack water sampling data for the same 4 days of the study period. The spatial profiles depicted in these figures indicate that the model was predicting dye movement and concentration buildups satisfactorily. While simulated

* As indicated previously, the actual dispersion coefficient is computed internally from the relationship

$$E = C_4 U d$$

where $C_4$ is a constant, U is the mean velocity, and d is the depth

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY
NOVEMBER 6, 1969

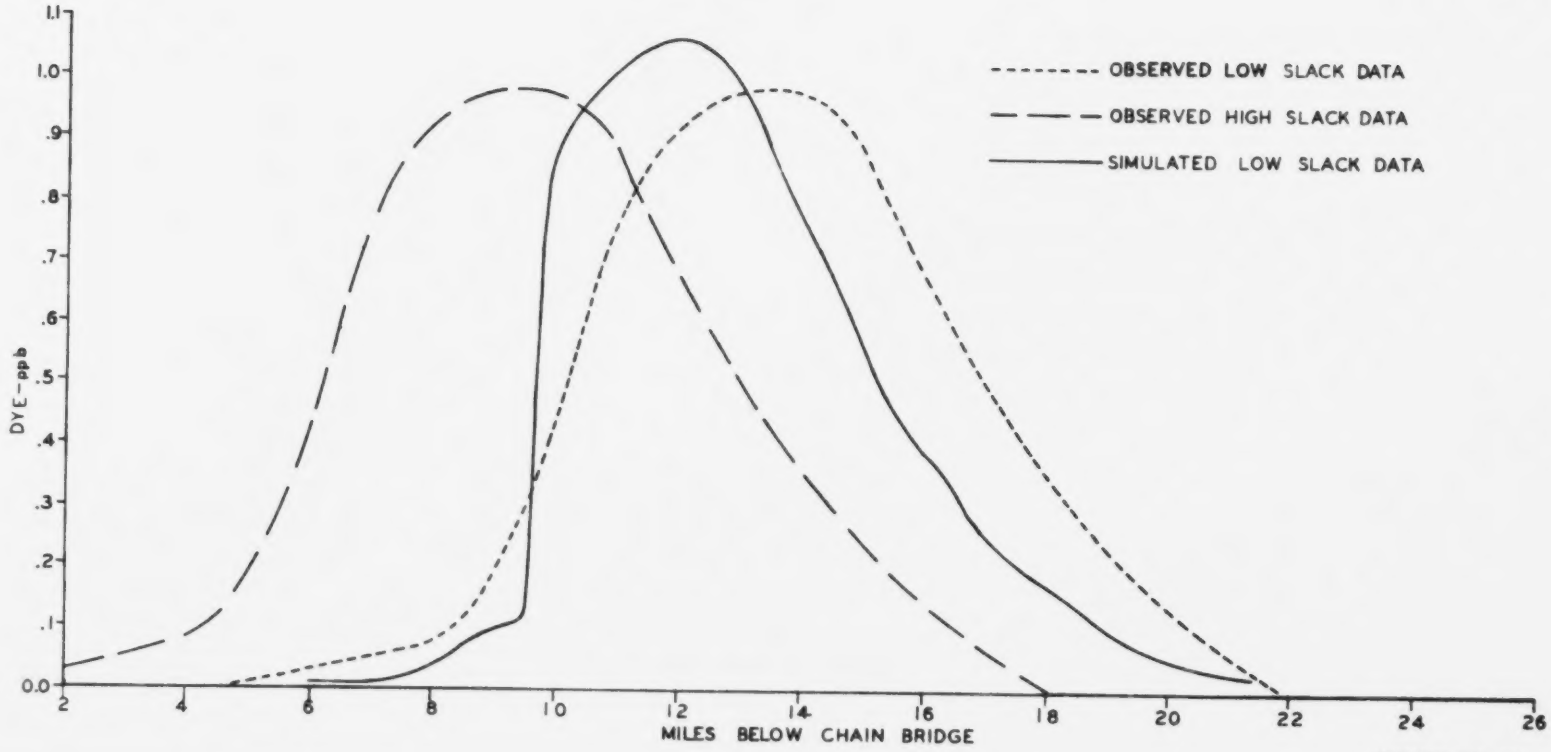



FIGURE V-13

FWQA DYNAMIC ESTUARY MODEL

DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 10, 1969

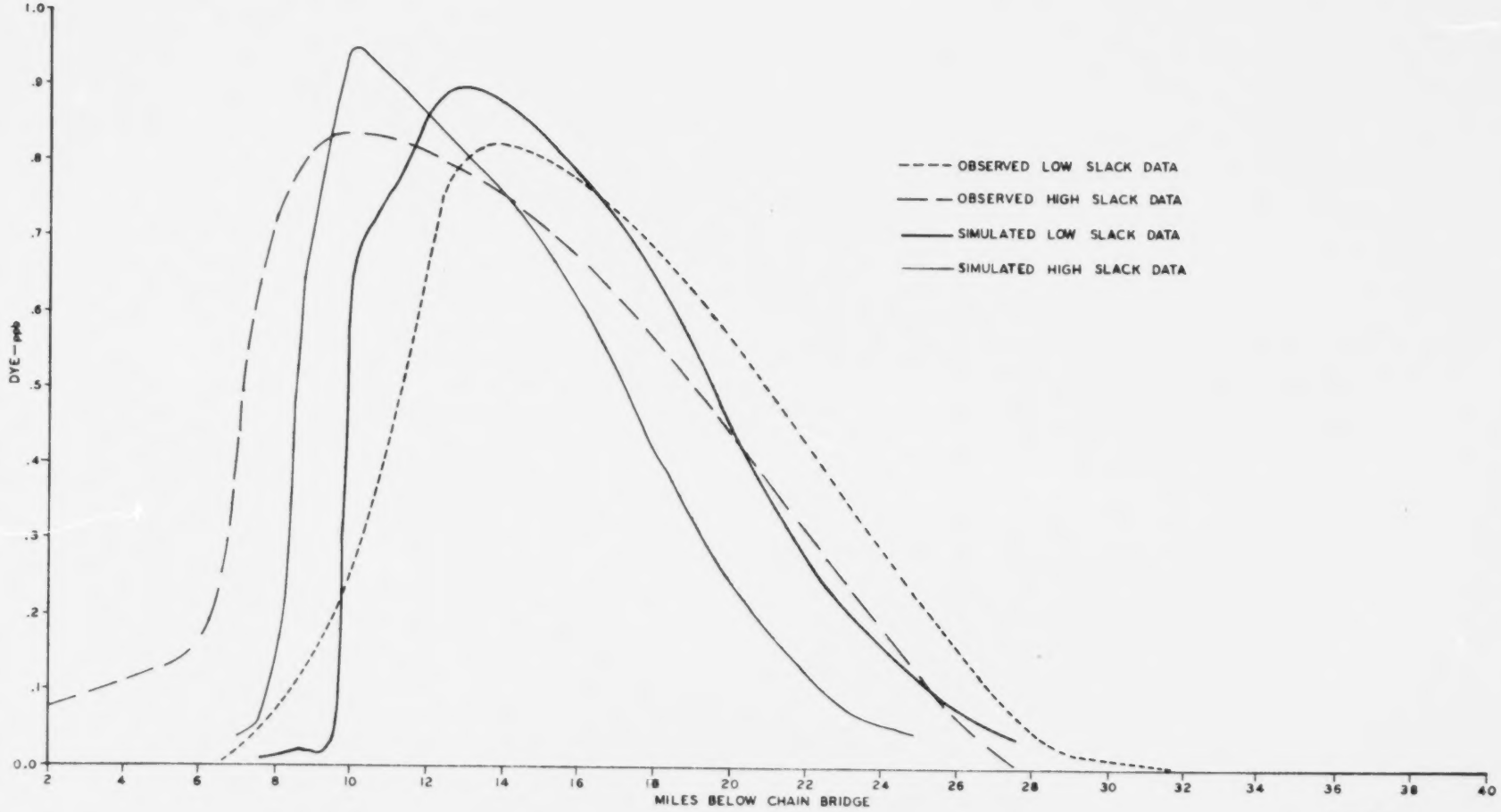



FIGURE II-14

FWQA DYNAMIC ESTUARY MODEL

DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 12, 1969

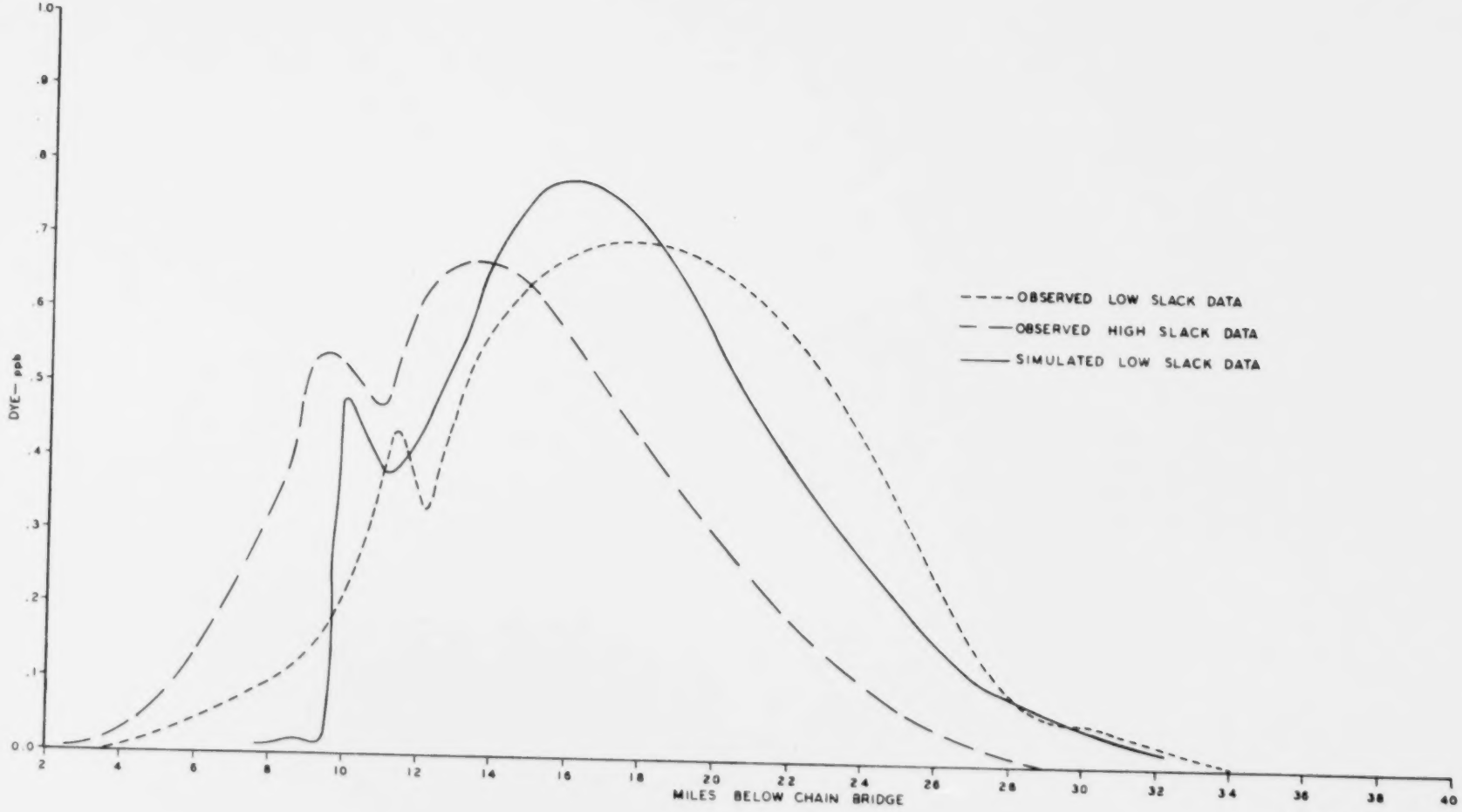



FIGURE IX- 15

FWQA DYNAMIC ESTUARY MODEL

DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 17, 1969

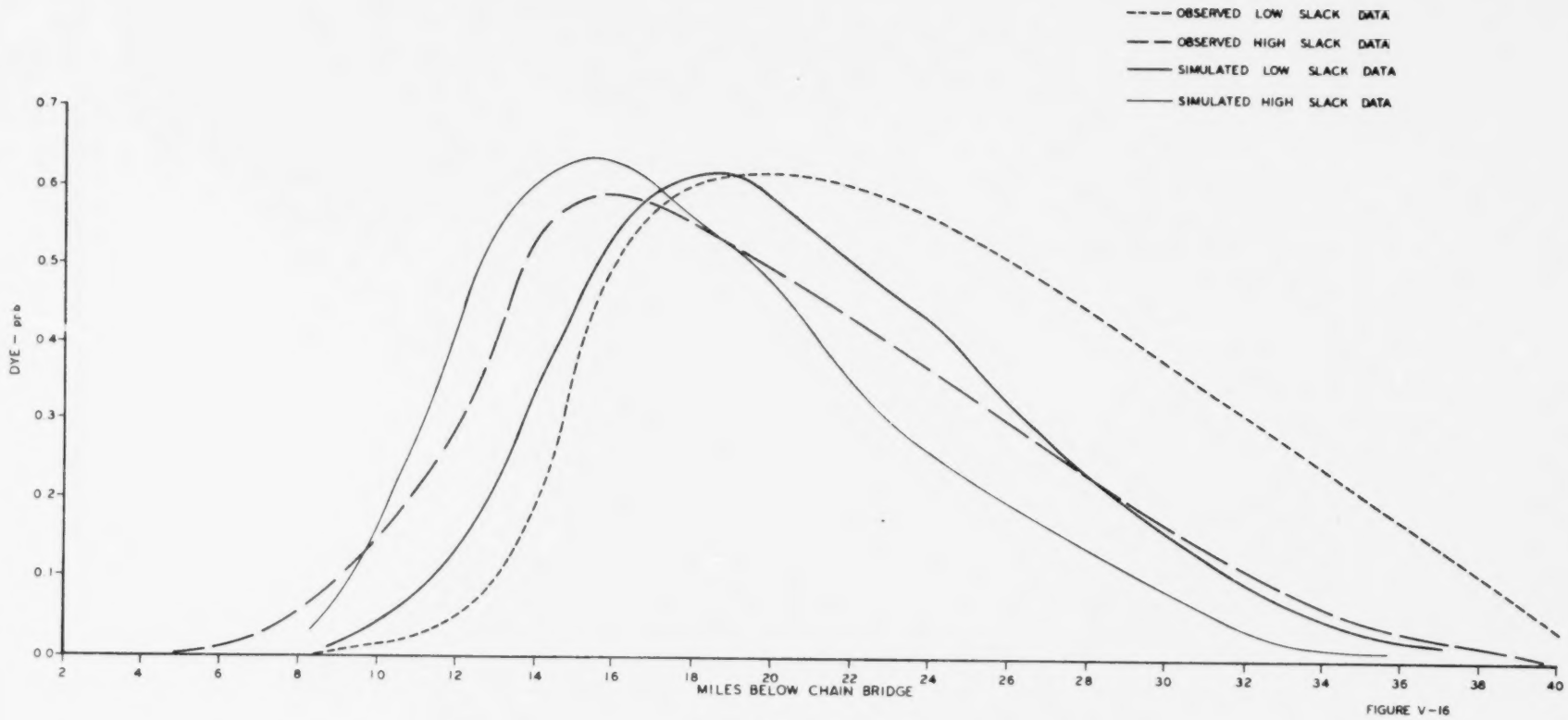



FIGURE V-16

# TEMPORAL DYE PROFILES
# UPPER POTOMAC ESTUARY
## FWQA DYNAMIC ESTUARY MODEL
(HIGH WATER SLACK DATA)

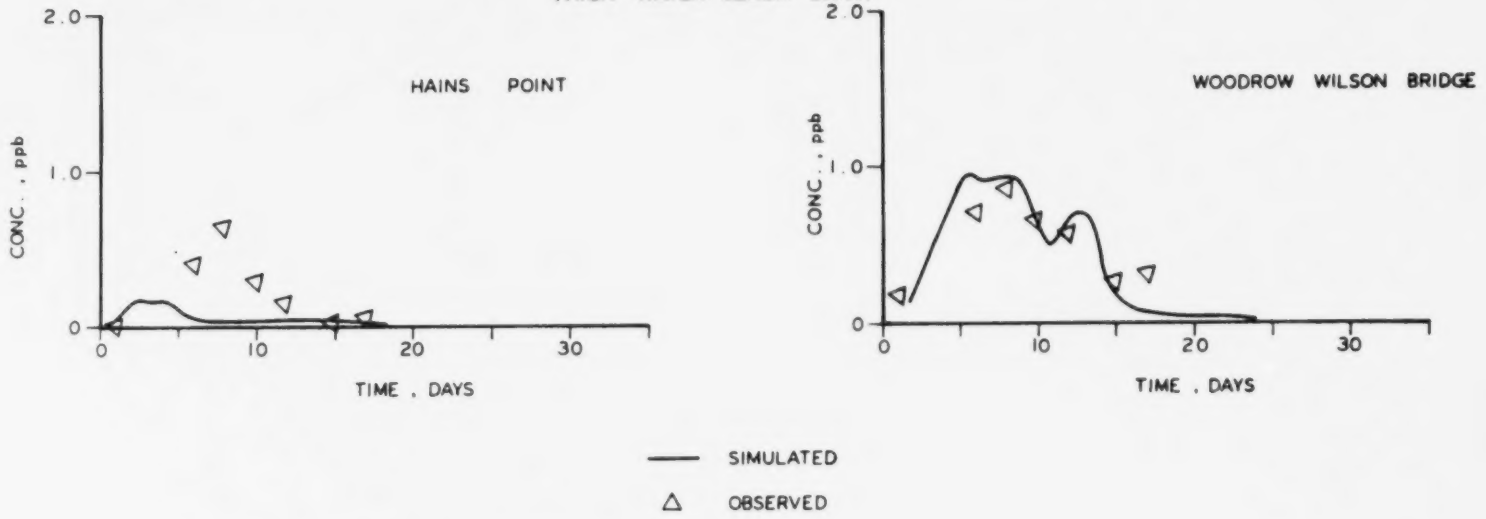



FIGURE V-17

# TEMPORAL DYE PROFILES
## UPPER POTOMAC ESTUARY
### FWQA DYNAMIC ESTUARY MODEL
(LOW WATER SLACK DATA)

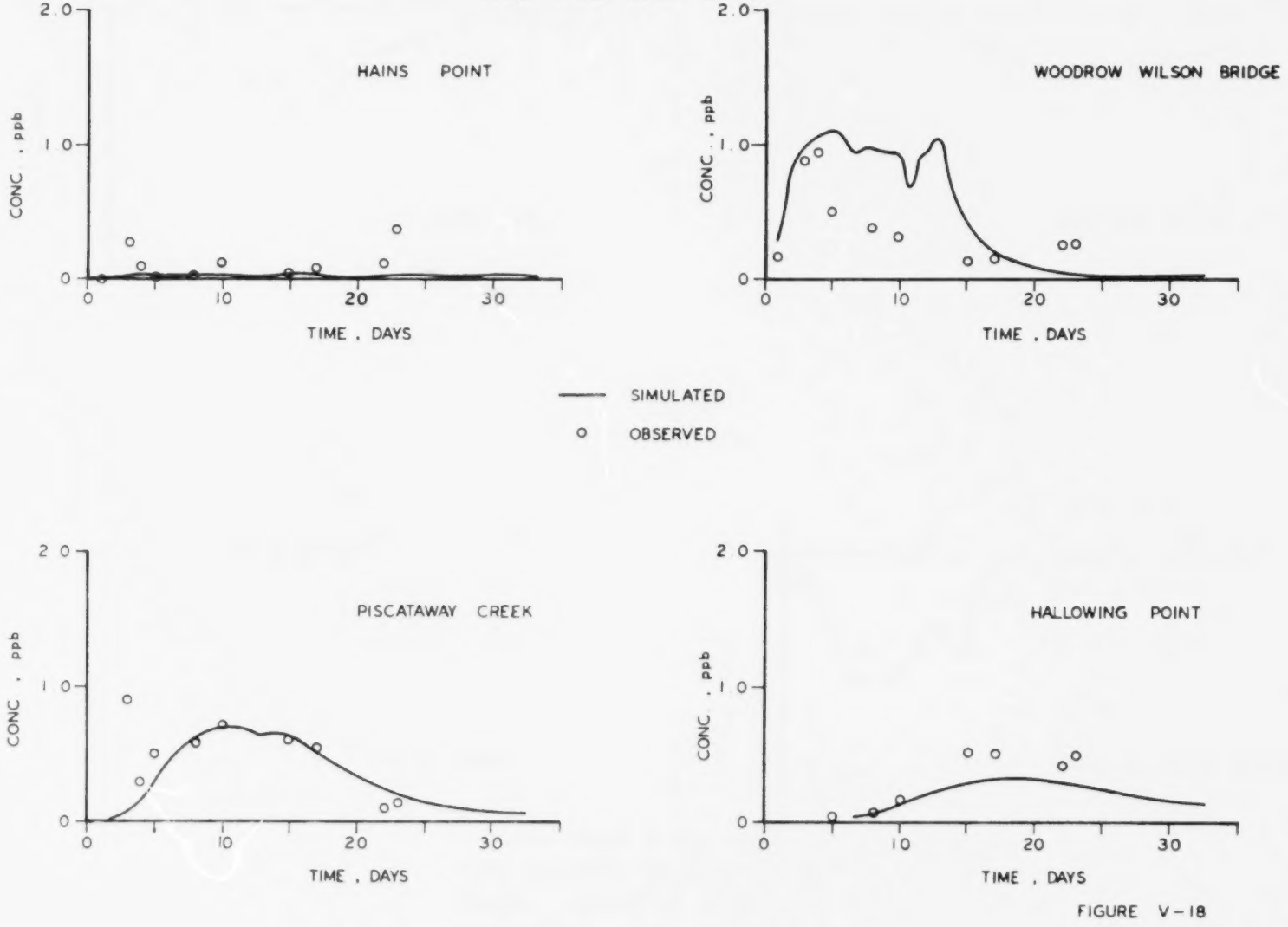



FIGURE V-18

maximum dye concentrations were generally higher than prototype data, they were not characterized by the pronounced "peaking" which occurred with Thomann Model simulations and their spatial position agreed favorably with observed data. The other consistent difference between the observed and simulated profiles was the insufficient downstream dye transport by the model over a given time interval. It is interesting to note that a "real-time" solution permitted the effects of a short term dye slug to be simulated as can be seen in Figure V-15. Considering the difficulty of model verification by a comparison of spatial profiles for specific slack-tide periods, the Dynamic Estuary Model has demonstrated the capability to simulate the hydraulic and quality behavior in the Potomac acceptably utilizing 1969 dye study data. Similar agreement between model and prototype data can be shown when temporal variations are considered. Data of this type (station histories) are presented in Figures V-17 and V-18.

b. Anacostia Dye Study

The physical network of junctions applied to the Anacostia tidal river for the Dynamic Estuary Model is shown in Figure V-1. This network is identical to the one used in the Thomann Model and is comprised of 15 junctions with lengths averaging approximately 1/2 mile.

For all hydraulic simulations during the study period, an average Potomac tide (12.5-hour period) was estimated from data recorded by the U. S. Coast and Geodetic Survey at Piney Point. Some degree of hydrodynamic verification was lacking due to the absence of tidal gaging stations in the Anacostia River. Visual observations of the tidal range near the point of dye release and the model's tidal range predictions appeared to be of similar magnitude; however, it could not be determined whether the simulation of tidal phasing and duration of rise and fall throughout the Anacostia, or even the assumed Manning roughness coefficients were accurate.

The dye study period was divided into four separate hydraulic components as follows:

| Time Period | Average Potomac Flow (cfs) | Average Anacostia Flow (cfs) |
|---|---|---|
| April 20-28 | 30,000 | 180 |
| April 29-May 11 | 15,000 | 83 |
| May 12-18 | 7,800 | 145 |
| May 19-28 | 6,800 | 72 |

The quality program for the Anacostia study was based on a constant dye loading rate of 8.1 lbs/day, a dye loss rate of 0.05/day and a uniform background concentration of 0.10 ppb. Moreover, the dispersion term, $C_4$, was assigned a value of 25.0. The dye profiles observed during various days of the study and corresponding simulated data from the Dynamic Estuary Model are shown in Figures V-19 through V-23. While the general longitudinal dye distribution predicted by the model compared favorably with prototype data, several figures were characterized by insufficient downstream movement of simulated peak concentrations. On one occasion (Figure V-19), the magnitude of the simulated peak was excessive. A further evaluation of the input factors which may have influenced these differences such as network geometry or dye loading rates was made but with no apparent success. It appeared that a lack of tidal data during the study period may have been partially responsible, otherwise a better hydraulic representation would have been obtained. Another possible cause of the differences noted could have been the flow averaging concept used for each hydraulic simulation. This averaging may tend to disregard or minimize the effects of the "flashy" flows that occurred during the early phase of the study.

Improved agreement may have been realized in both models had transect sampling data been collected to correlate mid-channel concentrations with cross-sectional averages. Normally, the differences resulting from this omission would be especially acute near the release point where incomplete mixing could be expected and where most of the model verification difficulties were encountered.

# FWQA DYNAMIC ESTUARY MODEL
## DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER
APRIL 23, 1970

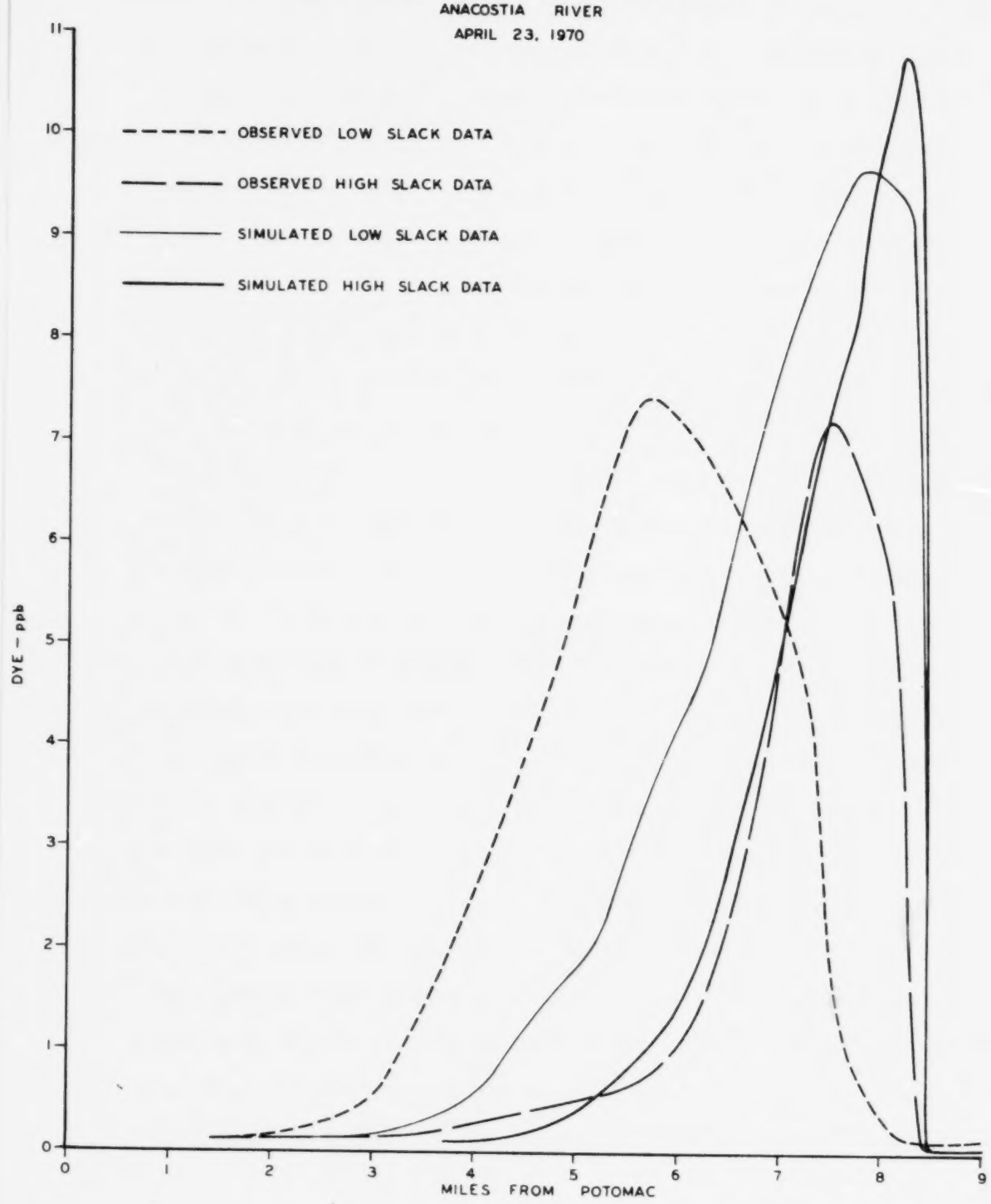



FIGURE V-19

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

ANACOSTIA RIVER

APRIL 27, 1970

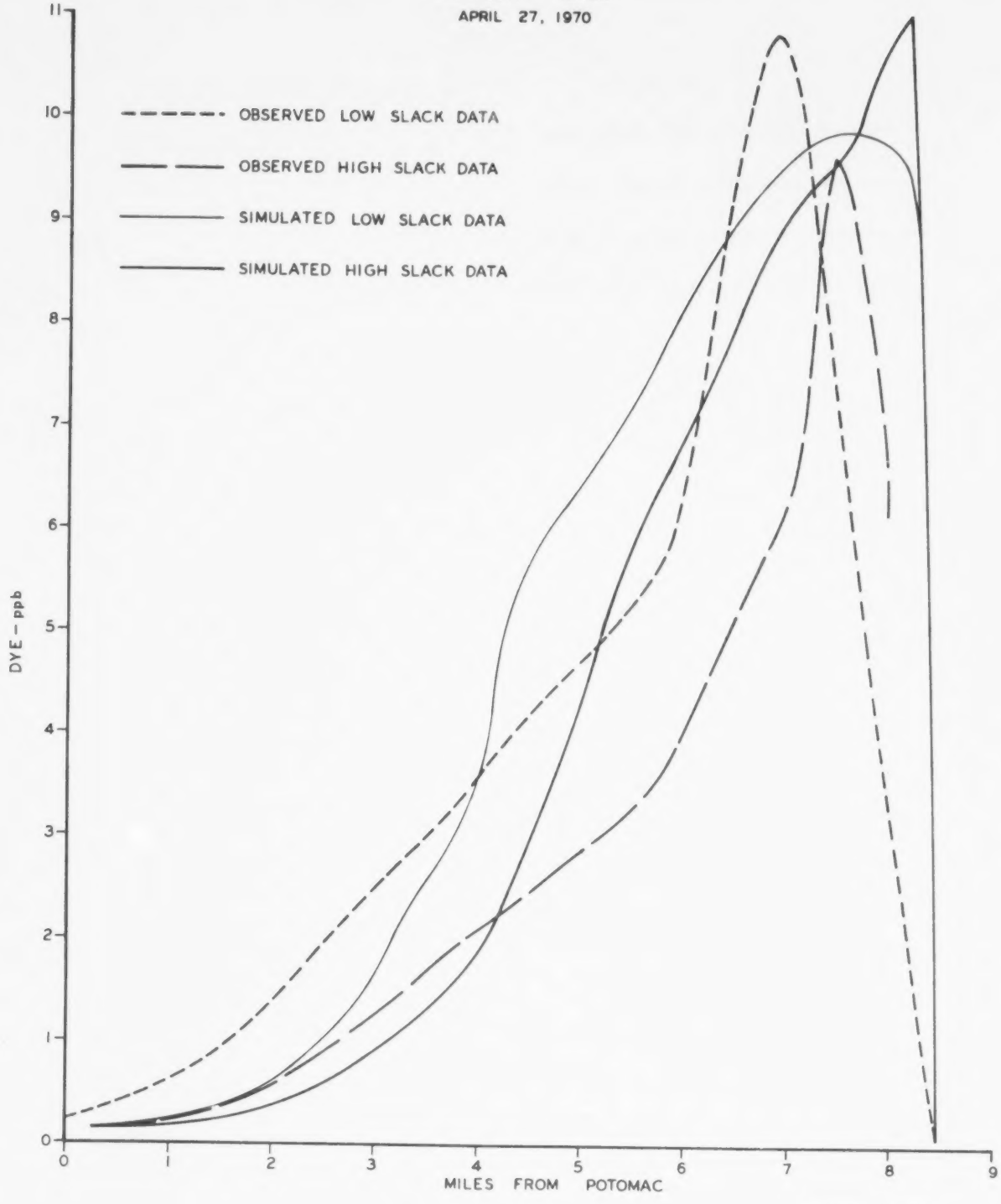



FIGURE V-20

# FWQA DYNAMIC ESTUARY MODEL
## DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER
APRIL 29, 1970

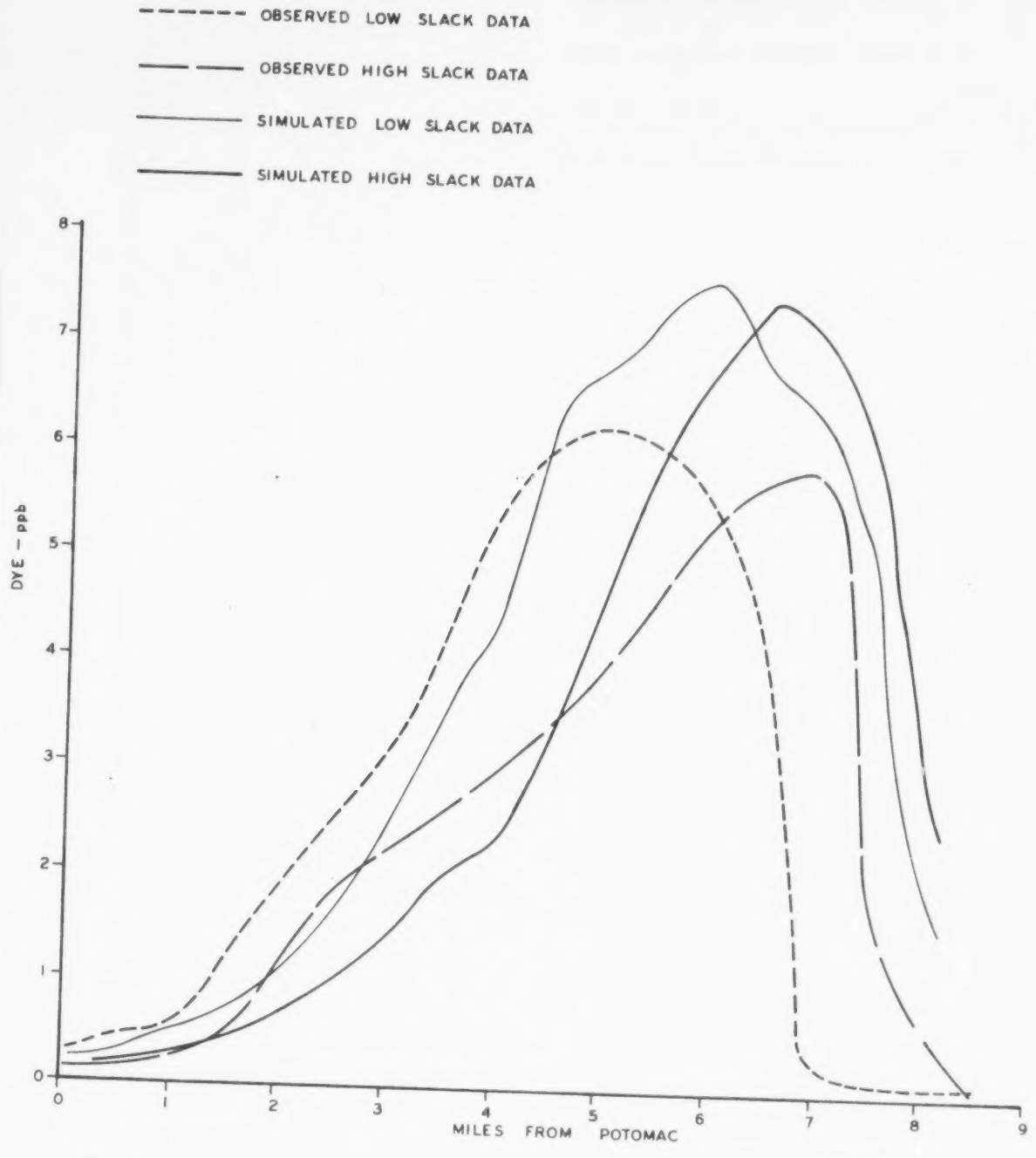



FIGURE V-21

# FWQA DYNAMIC ESTUARY MODEL
## DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER
MAY 4 , 1970

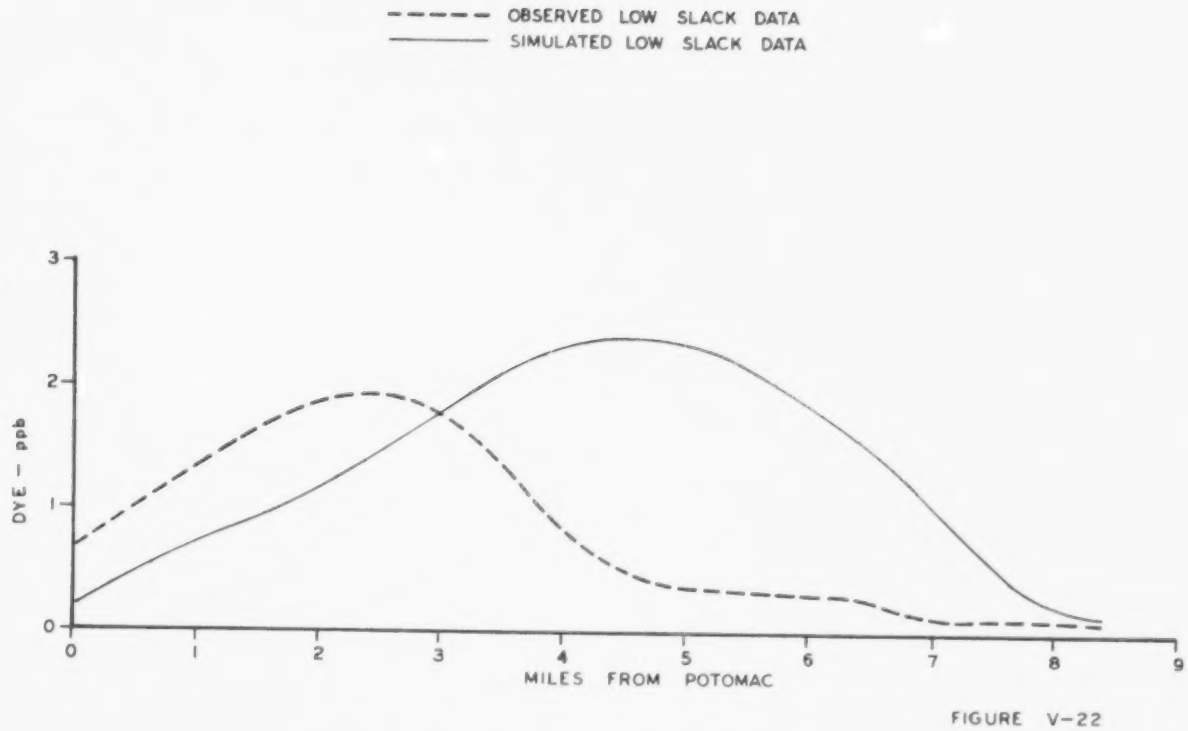



FIGURE V-22

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

ANACOSTIA RIVER

MAY 7 , 1970

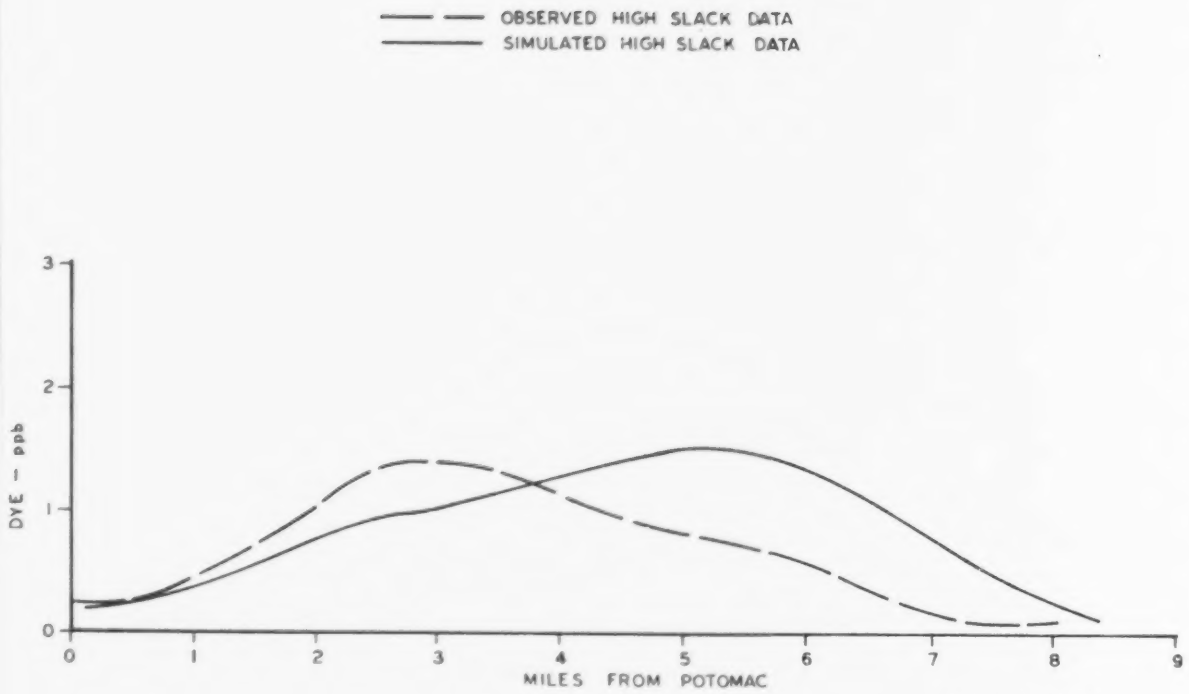



FIGURE V-23

# CHAPTER VI

# OTHER MATHEMATICAL MODEL SIMULATIONS

## A. SIMULATION OF 1969 DYE RELEASE

The 1965 dye release data were incorporated in a series of model runs for verifying both the Thomann and Dynamic Estuary mathematical models under a different hydraulic regime than that which occurred during the November 1969 dye study. The freshwater inflow rates during the 1965 study period (June 10-July 15) averaged about 2,000 cfs, or approximately one-half of the average November 1969 flows. Because of this lower flow, the appropriate dispersion coefficients required to verify the Thomann Model were expected to be significantly different.

### 1. Thomann Model

Figures VI-1 through VI-4 show the observed high- and low-slack water sampling data for various days and the corresponding simulated mean tide data using the Thomann Model. A dispersion coefficient of 2.0 $mi^2$/day was used initially when flows were relatively high, and 1.0 $mi^2$/day for the remainder of the study period when flows were much lower. Although other dispersion coefficients and different spatial variations were investigated for model verification, the above values appeared to yield the closest agreement. It should be noted that these coefficients were considerably higher than those obtained by Hetling and O'Connell [3] using an analog computer solution based on temporal or "station history" verification. Their computed dispersion coefficients varied between 0.2 - 0.6 $mi^2$/day for a similar reach of the upper Potomac Estuary.

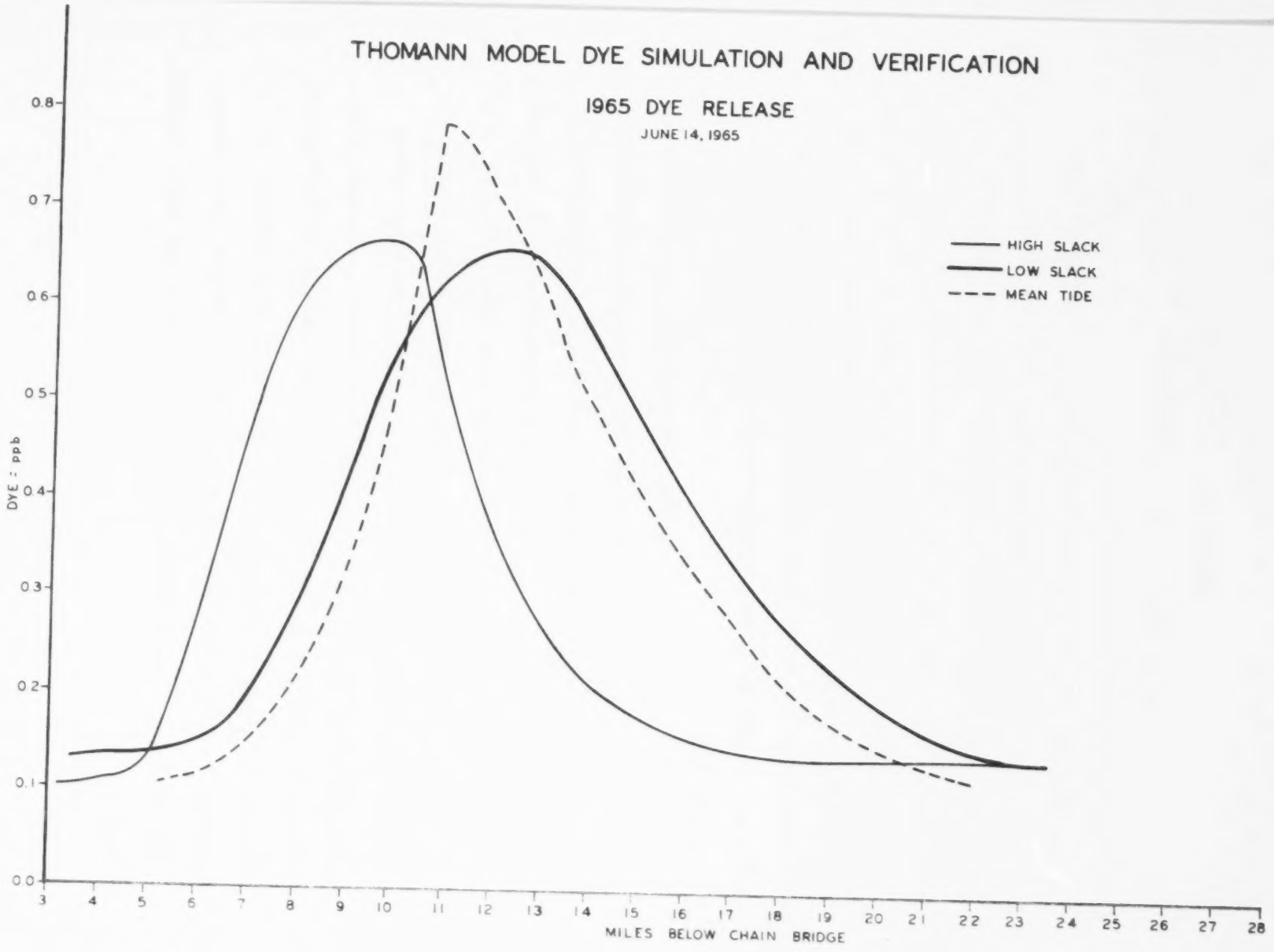

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JUNE 14, 1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE : ppb
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
MILES BELOW CHAIN BRIDGE

FIGURE VI-1

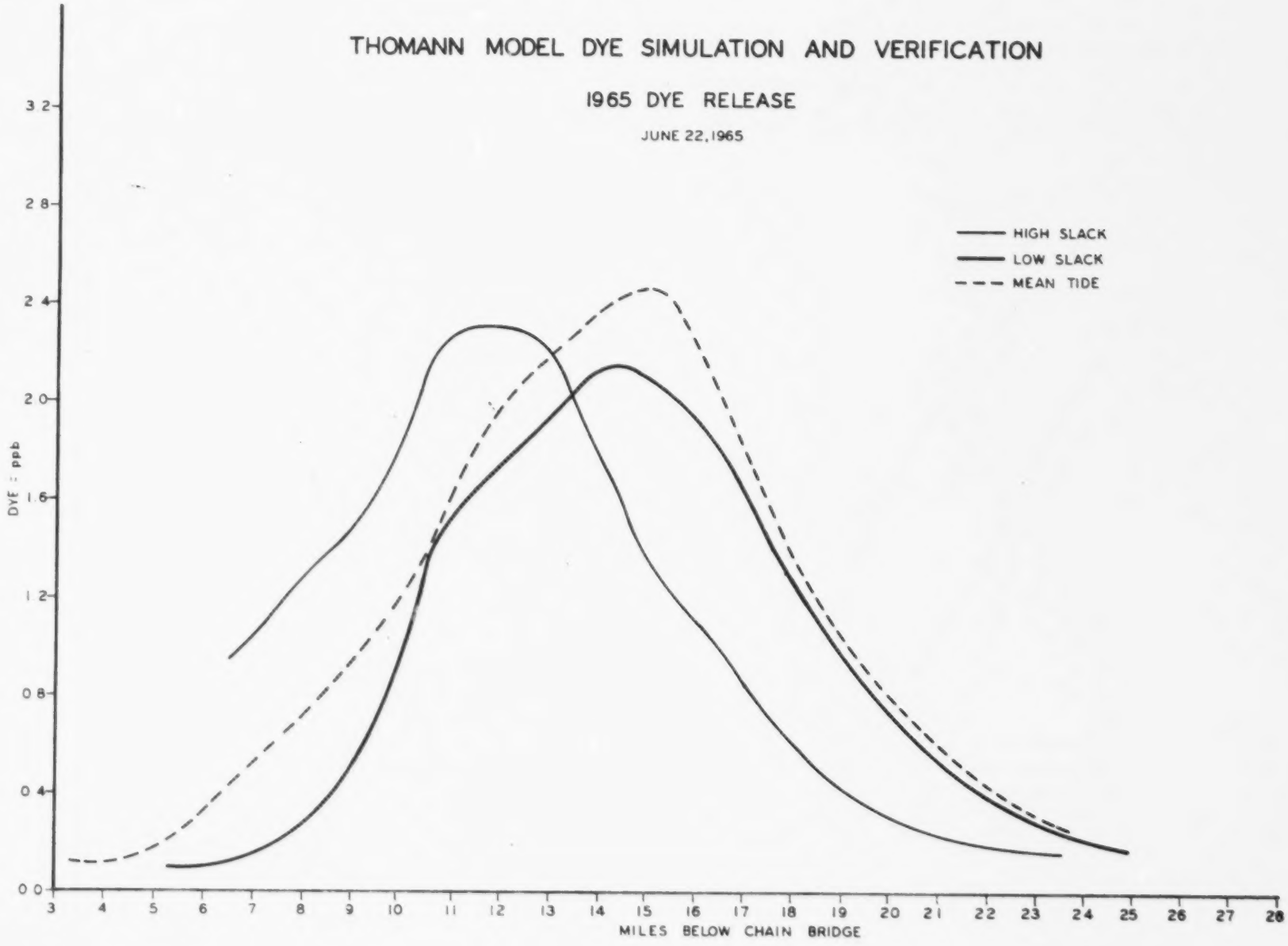

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JUNE 22, 1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE = ppb
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
MILES BELOW CHAIN BRIDGE

FIGURE XI– 2

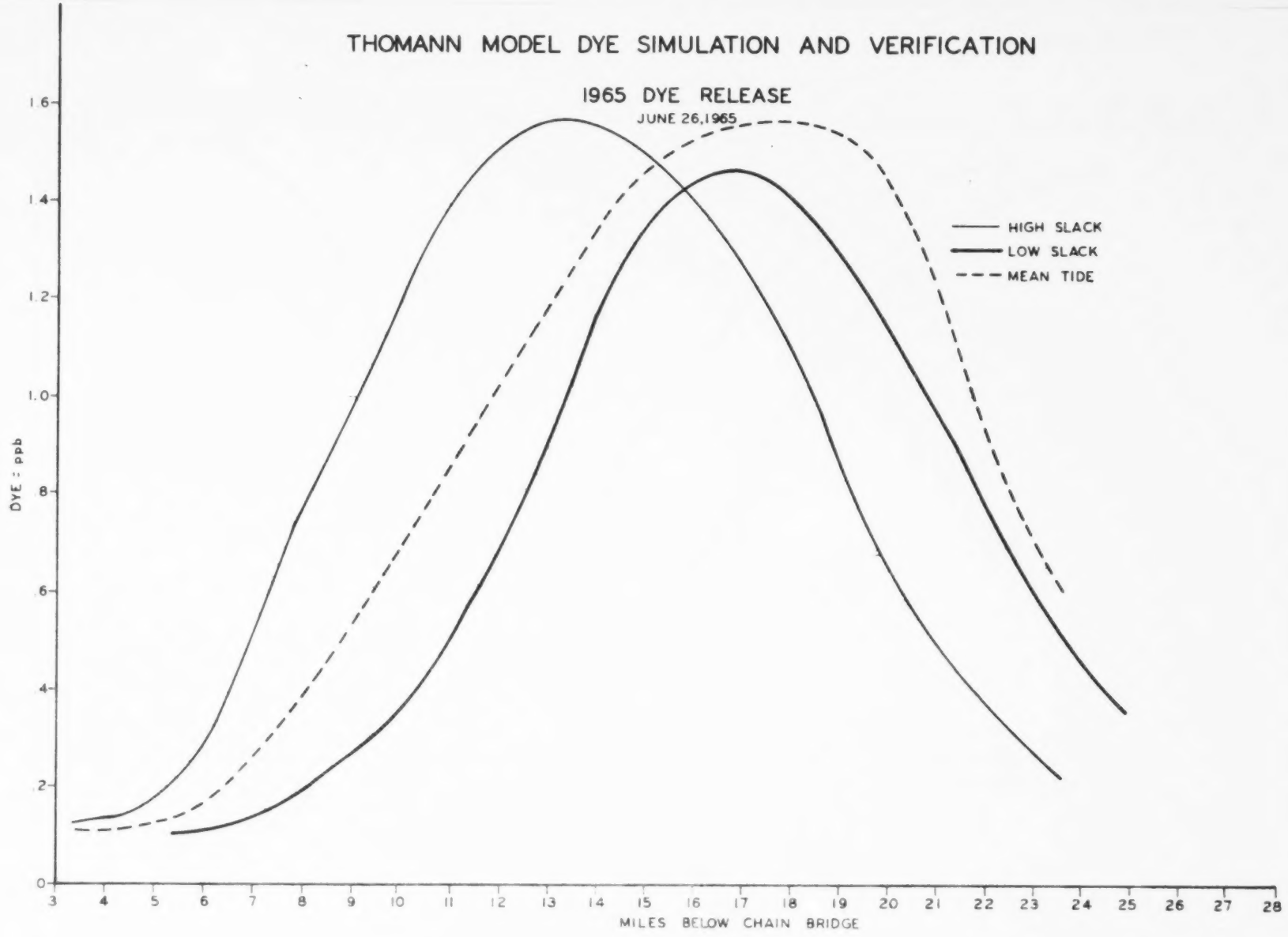

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JUNE 26,1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE : ppb
0
2
4
6
8
1.0
1.2
1.4
1.6
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
MILES BELOW CHAIN BRIDGE

FIGURE VI – 3

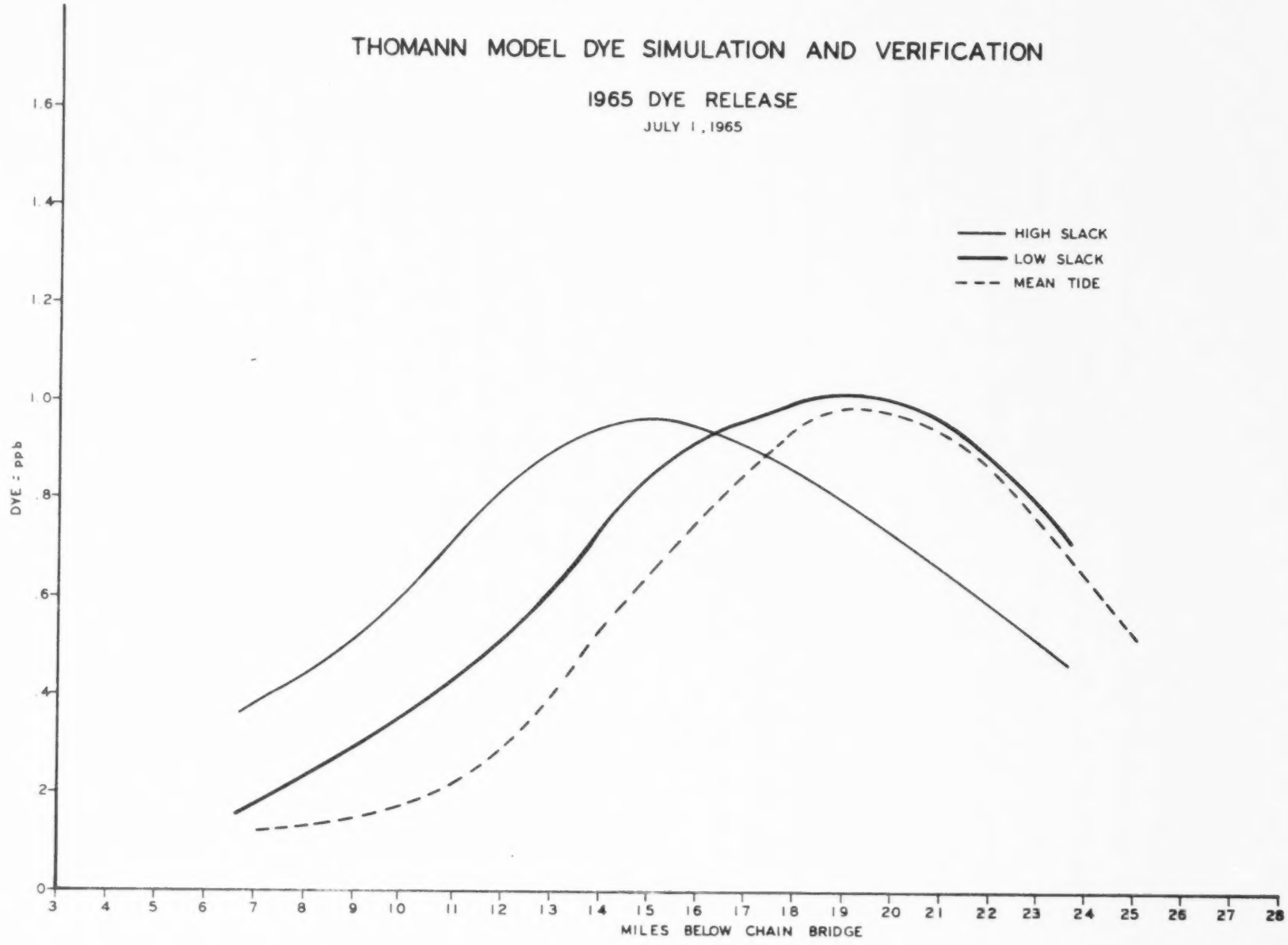

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JULY 1, 1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE : ppb
1.6
1.4
1.2
1.0
.8
.6
.4
2
0
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
MILES BELOW CHAIN BRIDGE

FIGURE XI-4

2. Dynamic Estuary Model

Two separate hydraulic conditions were assumed for the Dynamic Estuary Model when attempting to simulate the 1965 dye study data. Prior to June 23, the freshwater flow was assigned an average value of 2,687 cfs. The second hydraulic condition, which represented the remainder of the study period, was based on a constant flow of 1,451 cfs. In general, a steadily declining flow was experienced during this dye study.

The simulated 1965 dye profiles (high- and low-slack water) that resulted from using the Dynamic Estuary Model along with observed data are shown in Figures VI-5 through VI-8 for several days of the study period. An examination of these figures showed relatively close agreement in the spatial position, shape, and peak dye concentrations between the prototype and model data. However, in order for the observed and simulated dye mass characteristics to compare favorably, it was necessary to treat the dye as a conservative substance since applying a decay rate of either 0.034/day or 0.02/day in the model reduced the dye concentrations, and thus the mass, beyond an acceptable level. As will be pointed out in a subsequent chapter, the effects of decay rate are quite significant. The reason that this problem occurred in the mass balancing of prototype and model data cannot be explained except that the indeterminate fluorescent contribution from algae may have been responsible.

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

1965 DYE RELEASE

JUNE 14 1965

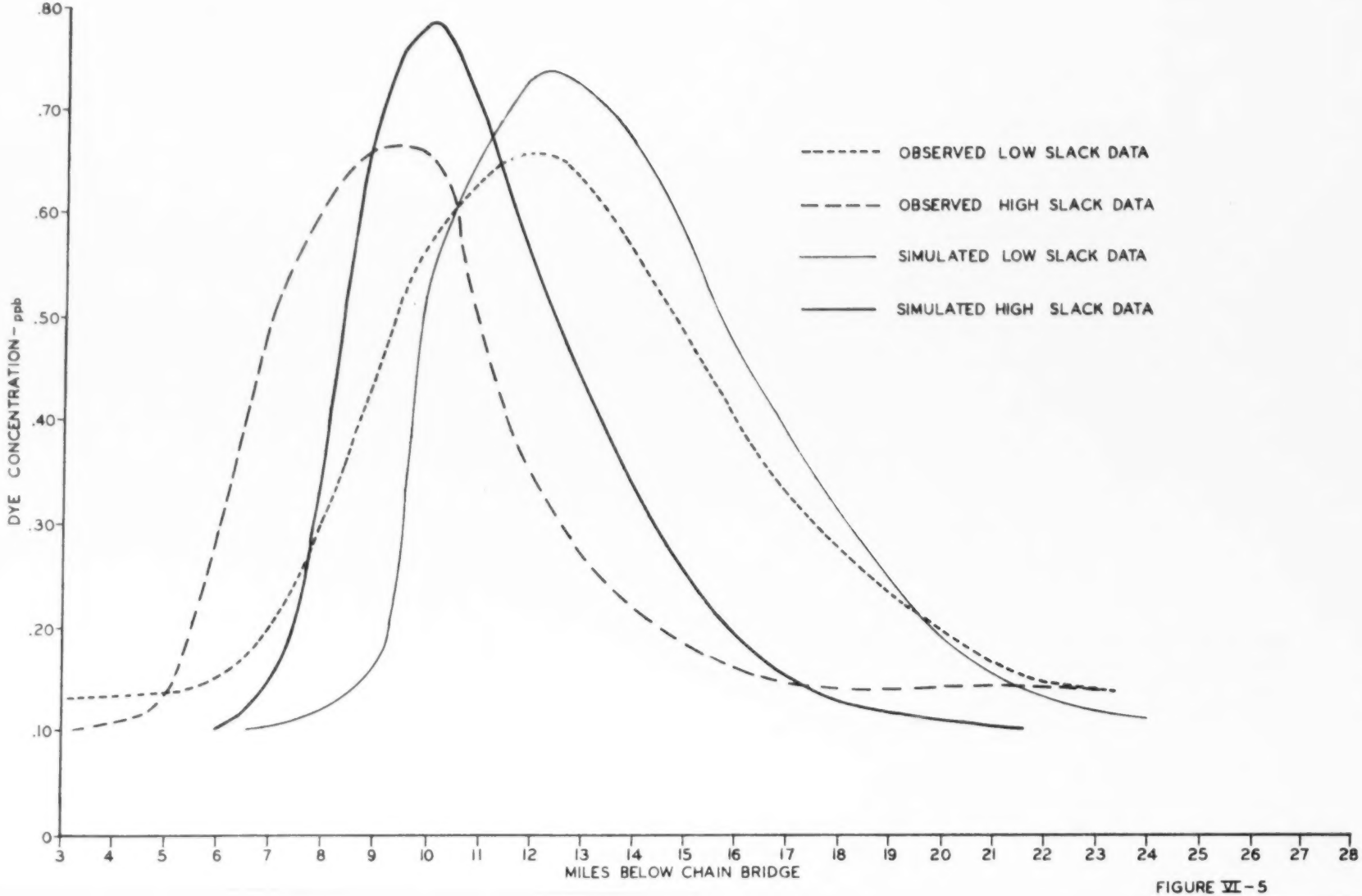



FIGURE VI-5

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

1965 DYE RELEASE

JUNE 26, 1965

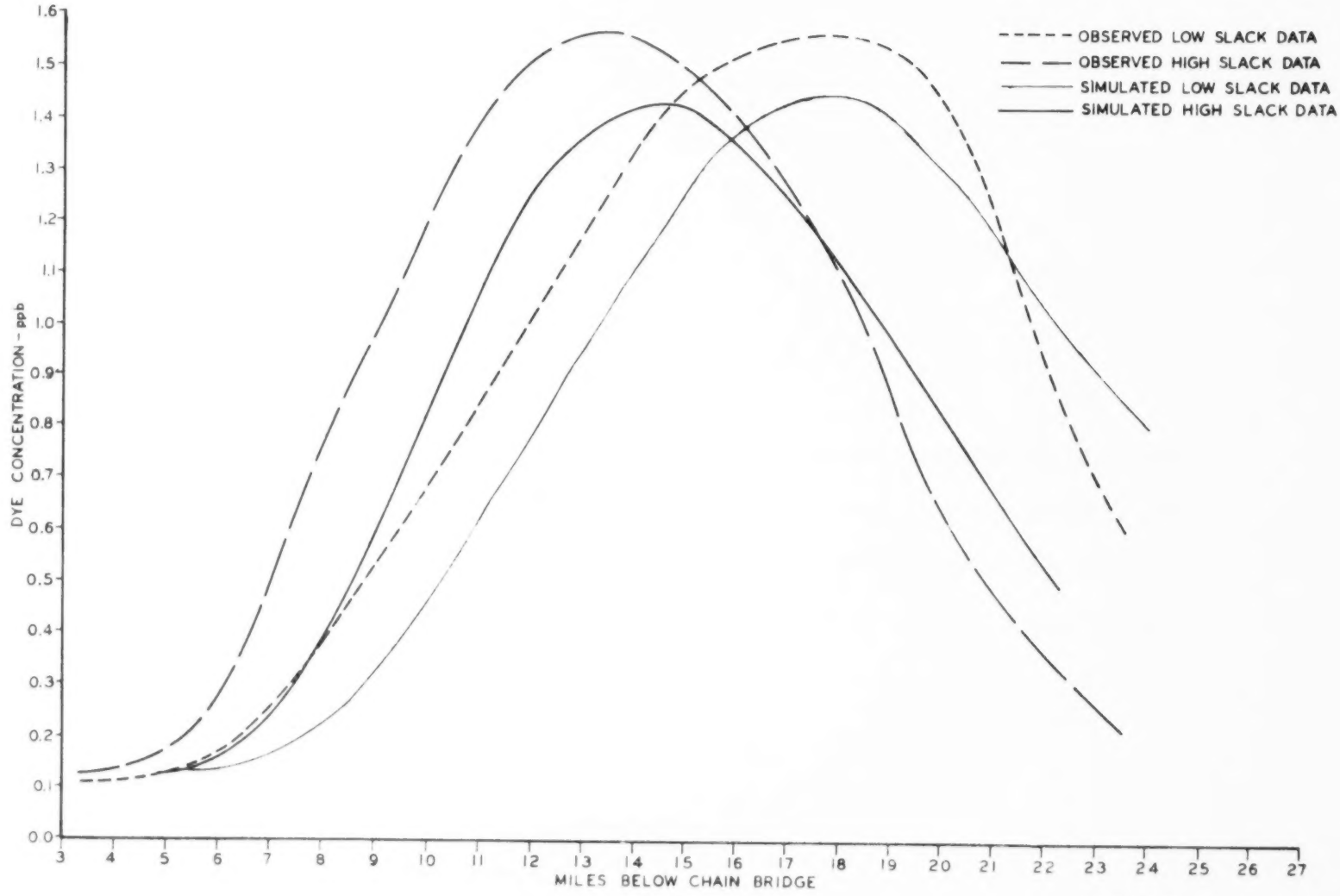



FIGURE VI-6

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

### 1965 DYE RELEASE

JULY 1, 1965

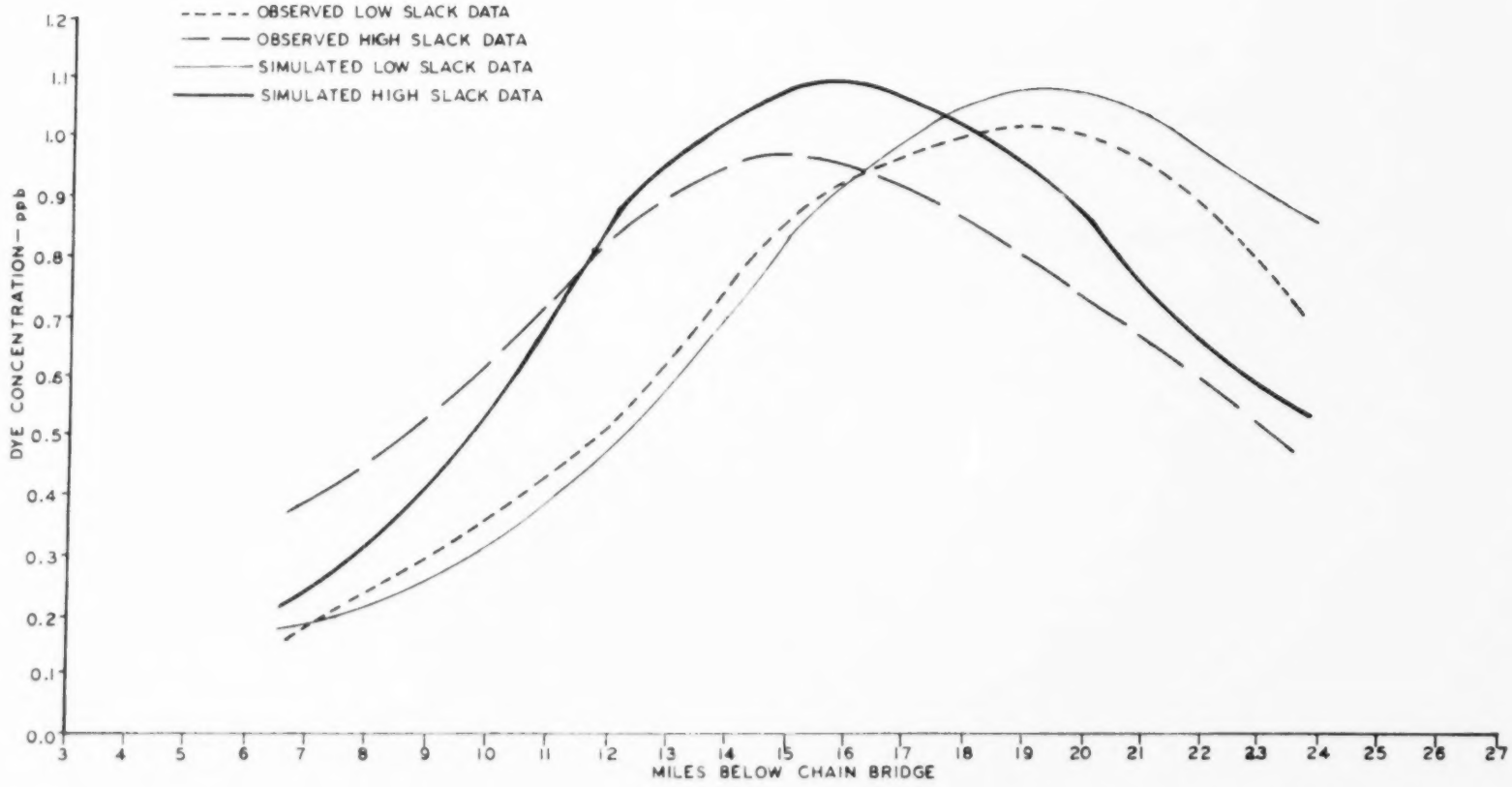



FIGURE VI-7

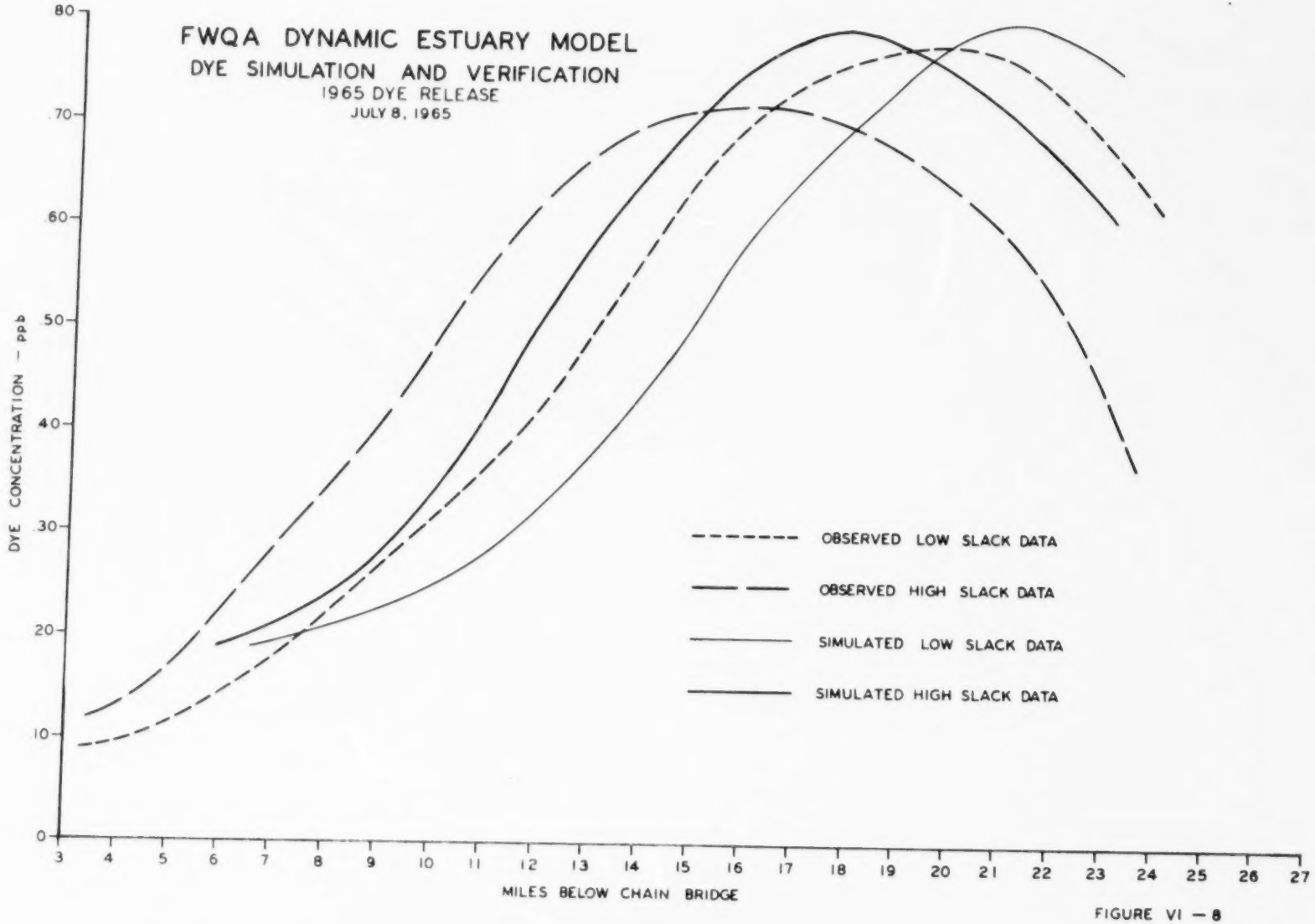

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JULY 8, 1965
DYE CONCENTRATION — ppb
0
10
20
30
40
50
60
70
80
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
MILES BELOW CHAIN BRIDGE
OBSERVED LOW SLACK DATA
OBSERVED HIGH SLACK DATA
SIMULATED LOW SLACK DATA
SIMULATED HIGH SLACK DATA

FIGURE VI — 8

B. CHLORIDE SIMULATIONS - 1966 AND 1969

1. Thomann Model

Further simulation and verification studies with the Thomann Model were made using 1966 and 1969 chloride data from the Potomac Estuary. It was believed that chloride data would provide a sound basis for estimating dispersion characteristics throughout the entire estuary rather than just the upper portion for which dye data was available. Moreover, the effects of density gradients created by varying chloride concentrations on dispersion rates could be evaluated.

The most complete temporal record of 1966 chloride concentrations in the Potomac was provided by the Virginia Electric and Power Company generating plant at Possum Point. These data along with the simulated chloride profiles at two representative model segments are shown in Figure VI-9. Observed and simulated profiles show reasonable agreement except for the almost continuous cyclic variation in the observed data. Two sets of dispersion coefficients were used in the Thomann Model for the 1966 chloride simulations. One set ranging from 2.0 - 20.0 $mi^2$/day was selected for the period January-May when freshwater inflows were usually between 11,000 and 14,000 cfs. The other set which ranged from 1.5 - 14.0 $mi^2$/day was used for the remainder of the year for 1,000 - 7,000 cfs inflows. The high range, of course, applied to the seaward portion of the estuary where maximum density differences could be expected.

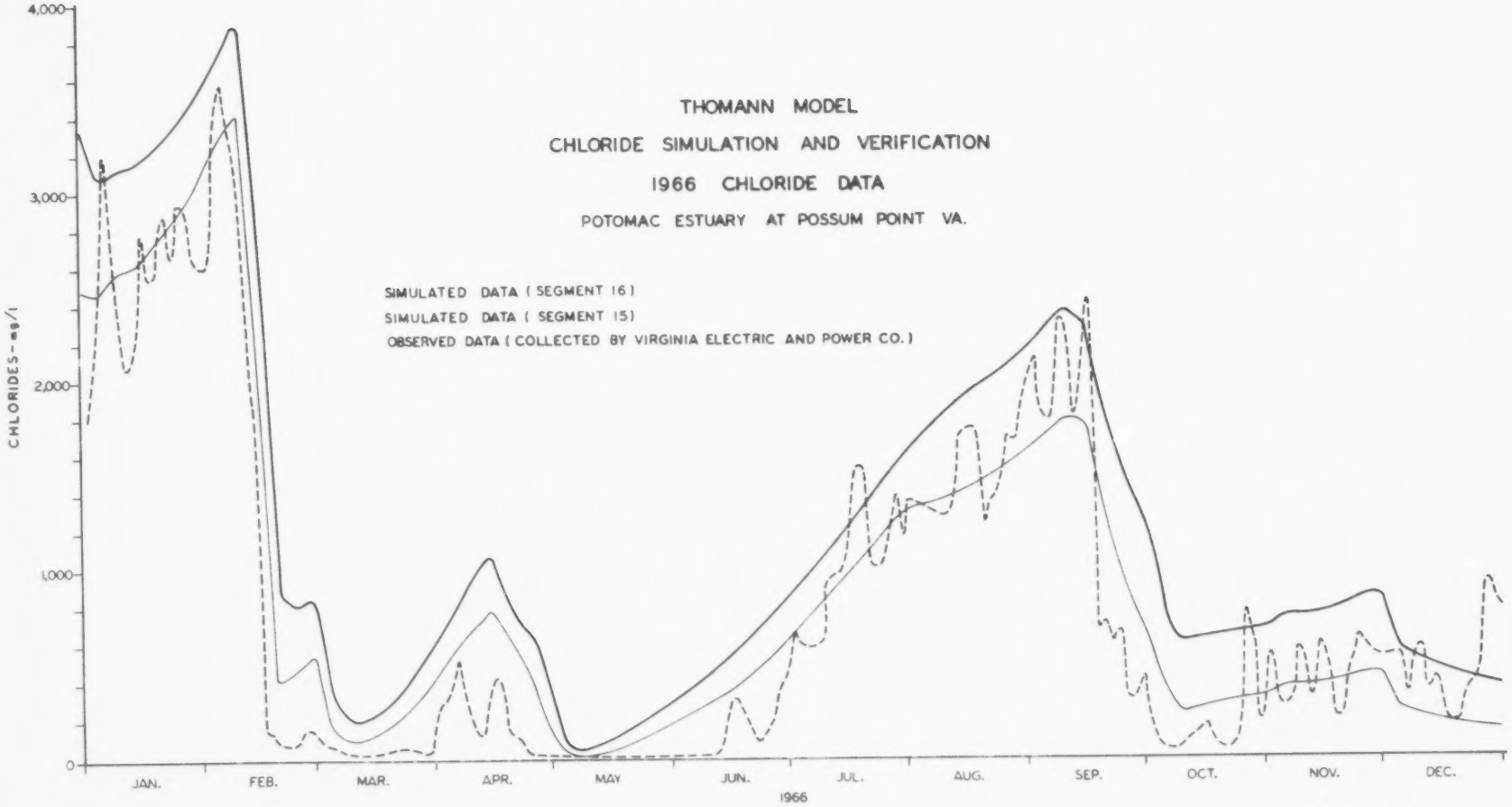

THOMANN MODEL
CHLORIDE SIMULATION AND VERIFICATION
1966 CHLORIDE DATA
POTOMAC ESTUARY AT POSSUM POINT VA.
SIMULATED DATA ( SEGMENT 16 )
SIMULATED DATA ( SEGMENT 15 )
OBSERVED DATA ( COLLECTED BY VIRGINIA ELECTRIC AND POWER CO. )
CHLORIDES - mg/l
4,000
3,000
2,000
1,000
0
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.
1966

FIGURE VI-9

Chloride concentrations at the upper boundary (Chain Bridge) were determined from D. C. Department of Sanitary Engineering sampling data. Seaward boundary values were correlated to U. S. Coast and Geodetic Survey data collected at Solomons, Maryland. Supplemental sampling data were obtained from a Potomac nutrient study conducted by the Chesapeake Bay Institute. The concentration of chlorides in wastewater discharges was assumed to be 40 mg/l.

A comparison of simulated and observed profiles showing 1969 chloride distributions is given in Figures VI-10 and VI-11 for sampling stations in the middle and lower reaches of the Potomac Estuary. The data as presented in these figures indicate relatively close agreement between model predictions and observed chloride profiles, again except for the day-to-day fluctuations in the observed data. Various sets of dispersion coefficients were tried in verifying the 1969 chloride data and the best agreement was obtained by using one set of coefficients ranging from 2.0 - 16.0 $mi^2$/day. It should be noted that use of a single set of coefficients departs from previous Thomann Model simulation studies discussed in this report wherein dispersion was found to be directly related to freshwater flow rates. While flows varied greatly during 1969, attempts to refine the dispersion coefficients to reflect these flow changes did not prove successful.

THOMANN MODEL

CHLORIDE SIMULATION AND VERIFICATION

1969 CHLORIDE DATA

POTOMAC ESTUARY AT NANJEMOY CREEK

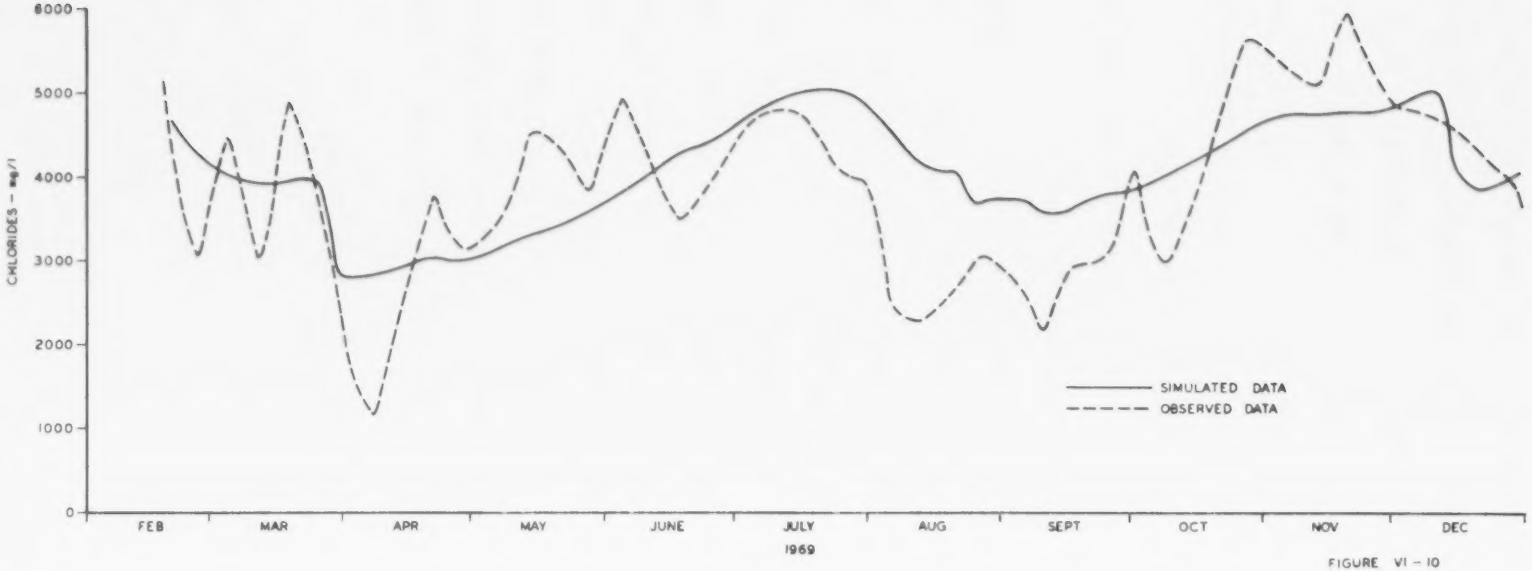



FIGURE VI - 10

THOMANN MODEL

CHLORIDE SIMULATION AND VERIFICATION

1969 CHLORIDE DATA

POTOMAC ESTUARY AT WICOMICO RIVER

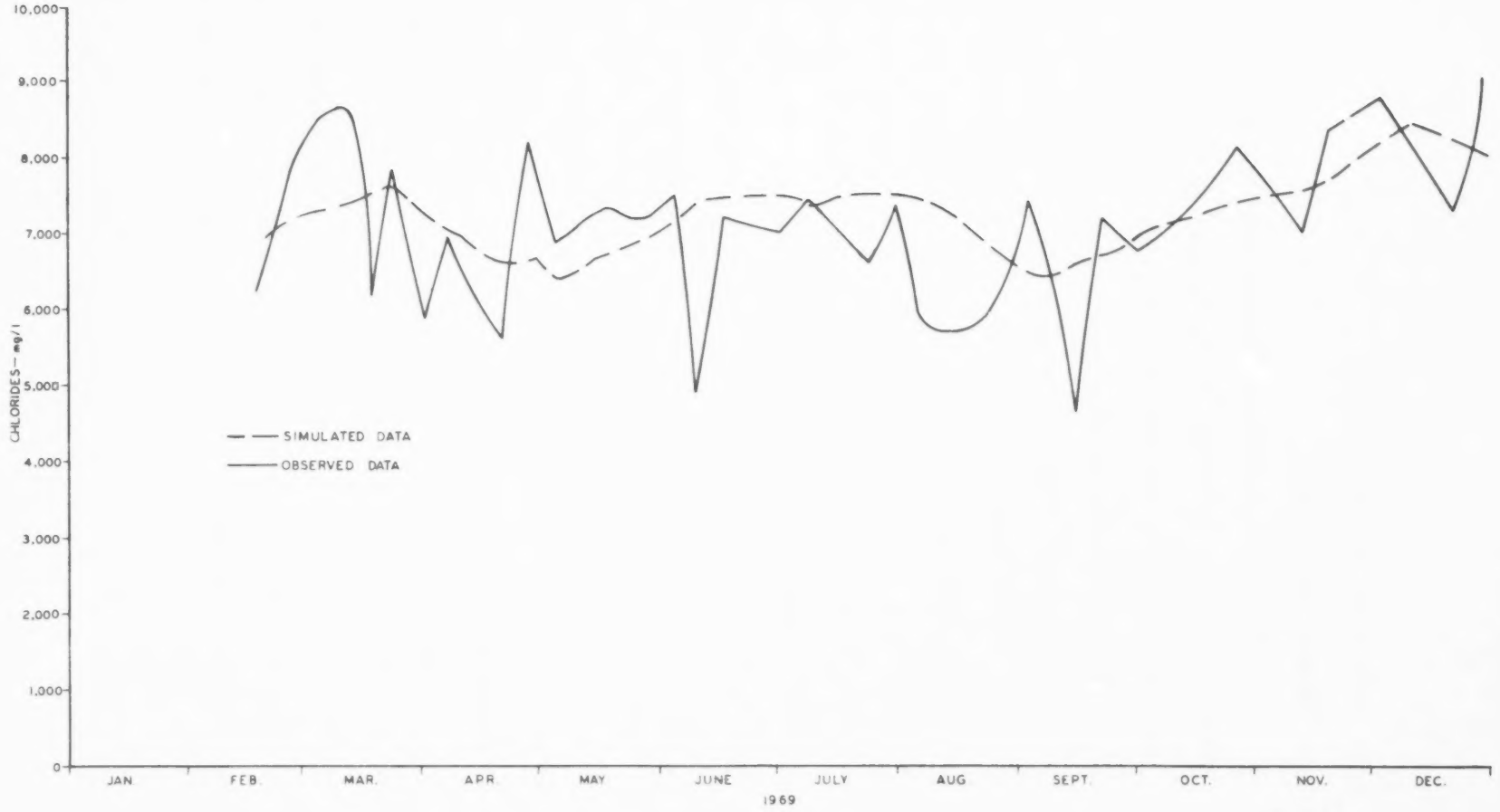



FIGURE VI — II

## C. SIMULATION OF 1965 CHLORIDES

### 1. Dynamic Estuary Model

To demonstrate the Dynamic Estuary Model's capability of simulating changing salinity conditions in the Potomac Estuary, an historical period (July-December 1965) was selected for which sufficient data were available to establish the salinity distribution throughout the system at two different points in time and for which flow rates were relatively uniform. The mean Potomac River flow over Great Falls remained near 1,300 cfs during this 5-month period with the mean monthly flows varying between 1,018 and 1,585 cfs. Data were available to establish the salinity profile in the main stem of the Potomac near the start of the period (July 7-8, 1965) and also near the end (December 1-2, 1965). These data were converted to chloride concentrations and were then utilized to establish visual "best fit" profiles for these two points in time as illustrated in Figure VI-12. No attempt was made to relate any specific data point to the tidal phase at the time of sampling, e.g., high- or low-slack water conditions; hence, the concentrations were assumed to be representative of the mean concentration over a full tidal cycle.

The profile for July 7-8, 1965, was specified as the initial profile in the model. For this simulation, the network extended to Piney Point, near River Mile 99. The specified chloride concentration at the seaward boundary was changed during the simulation to correspond to the change noted in the prototype during the same period, i.e., the concentration

# FWQA DYNAMIC ESTUARY MODEL
# CHLORIDE SIMULATION AND VERIFICATION
## POTOMAC ESTUARY
## JULY — DECEMBER, 1965

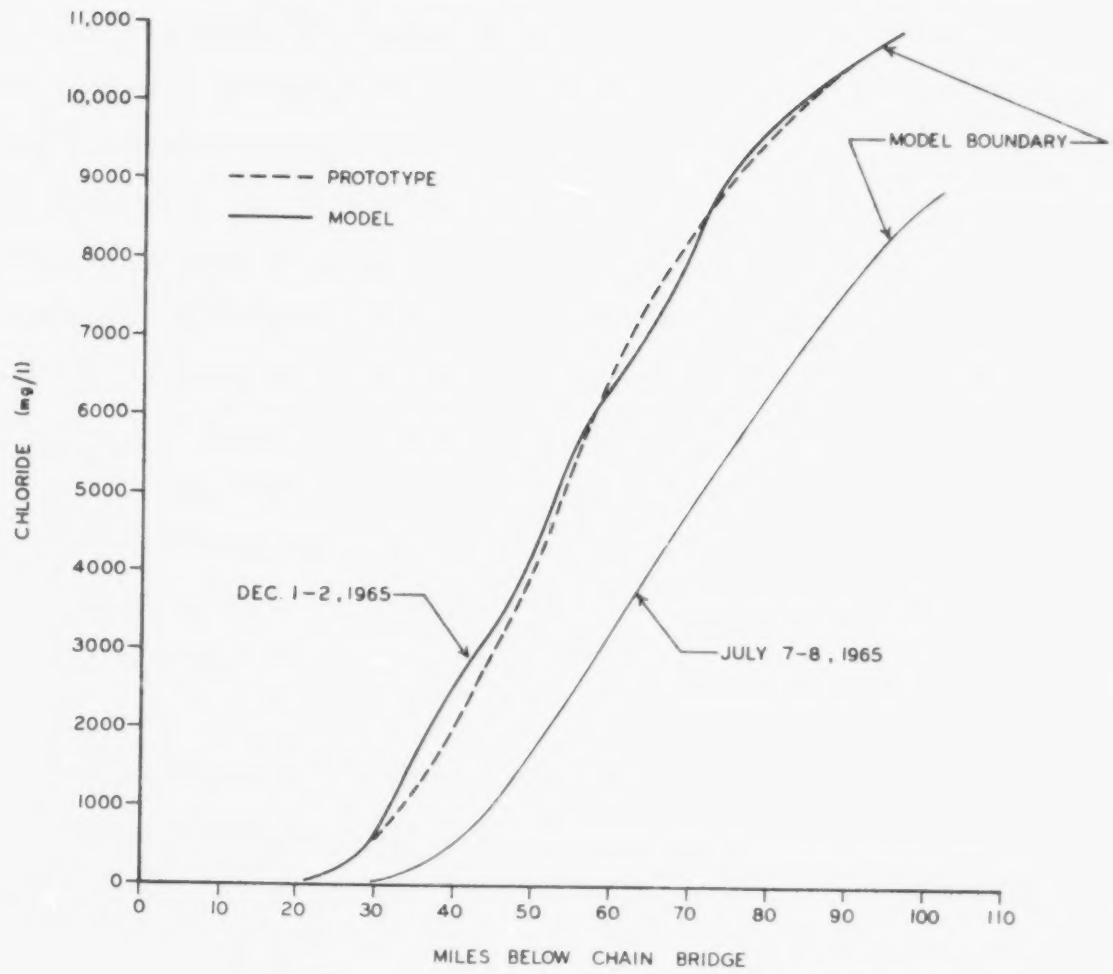



FIGURE VI - 12

was increased from 8,400 mg/l to 10,930 mg/l in increments of 55 mg/l every 3 days. A uniform flow of 1,300 cfs in the Potomac River was maintained in both the hydraulic and quality simulations.

The chloride profile predicted by use of the model after the 147-day simulation period is illustrated in Figure VI-12 along with that measured in the prototype. As can be seen, the upstream movement of the "salt wedge" and the spatial chloride distribution in the Potomac Estuary were successfully simulated for this 5-month condition.

In the course of model verification, certain unexpected problems arose which were related to the basic transport mechanisms, advection, and dispersion. These problems were evidently the result of simulating a constituent having an extremely high concentration gradient. For example, the standard one-quarter point method, i.e., the assigning of an advective concentration equal to that at one-quarter of the channel length measured in the direction of decreasing gradient, did not prove adequate. Although this solution technique for advective transport is acceptable in terms of numerical mixing, accuracy, and stability when simulating dye or other constituents with a small concentration gradient, the one-third point method yielded the best results with chlorides. A discussion of the Dynamic Estuary Model's sensitivity to the advective transport solution is included in Chapter VII.

The chloride simulation presented in Figure VI-12 was based on $C_4$ values of 15.0 (above River Mile 55), 80.0 (River Mile 55 to River Mile 70) and 250.0 (River Mile 70 to River Mile 99). Unlike previous simulations

where the rate of dispersion was considered constant throughout the system, it appeared that a strong relationship existed between dispersion rates and increased salinity gradients as suggested by Harleman [7]. A discussion of this aspect is also presented in Chapter VII.

It should be noted that an improved representation of the chloride distribution with less difficulty in defining the transport components of the model, including the transfer of chlorides across the seaward boundary, might have been realized had the model network been more refined in the lower portions of the Potomac Estuary. Almost all channels in this area were much wider than they were long, a distortion which could conceivably influence the chloride predictions obtained using the Dynamic Estuary Model.

# CHAPTER VII

# COMPARATIVE SENSITIVITY EVALUATIONS

# THOMANN AND DYNAMIC ESTUARY MODELS

## A. DECAY RATE OF POLLUTANT

The purpose of investigating the role of decay rate during mathematical modeling studies in the Potomac was essentially twofold: (1) to ascertain the effects of decay on the simulated distribution (steady state) of a pollutant by using both the Thomann and Dynamic Estuary Models and (2) to compare profiles from the two models for similar loading rates and freshwater flows for determining whether the predicted results agree, and what effect, if any, does decay rate exert on this agreement.

Figures VII-1 and VII-2 present steady-state simulated profiles from the Dynamic Estuary and Thomann Models, respectively, for decay rates varying from 0.0 to 0.4/day (base e), for a constant loading of 100,000 lbs/day, and for a flow of 4,430 cfs. As can be seen in these figures, each model's predictions are highly sensitive to the magnitude of the decay rate and each behaves similarly, i.e., lower peak concentrations and less mass transport, particularly downstream, as the decay rate increases. The major change in profiles occurs between decay rates of 0.0 (conservative) and 0.1/day. A further increase diminishes the effects of the decay rate in both models.

By comparing Figures VII-1 and VII-2, it is clearly evident that many similarities existed in the predictions from both models. Of particular importance was the close agreement obtained in peak magnitudes

## EFFECTS OF DECAY RATES
### DYNAMIC ESTUARY MODEL

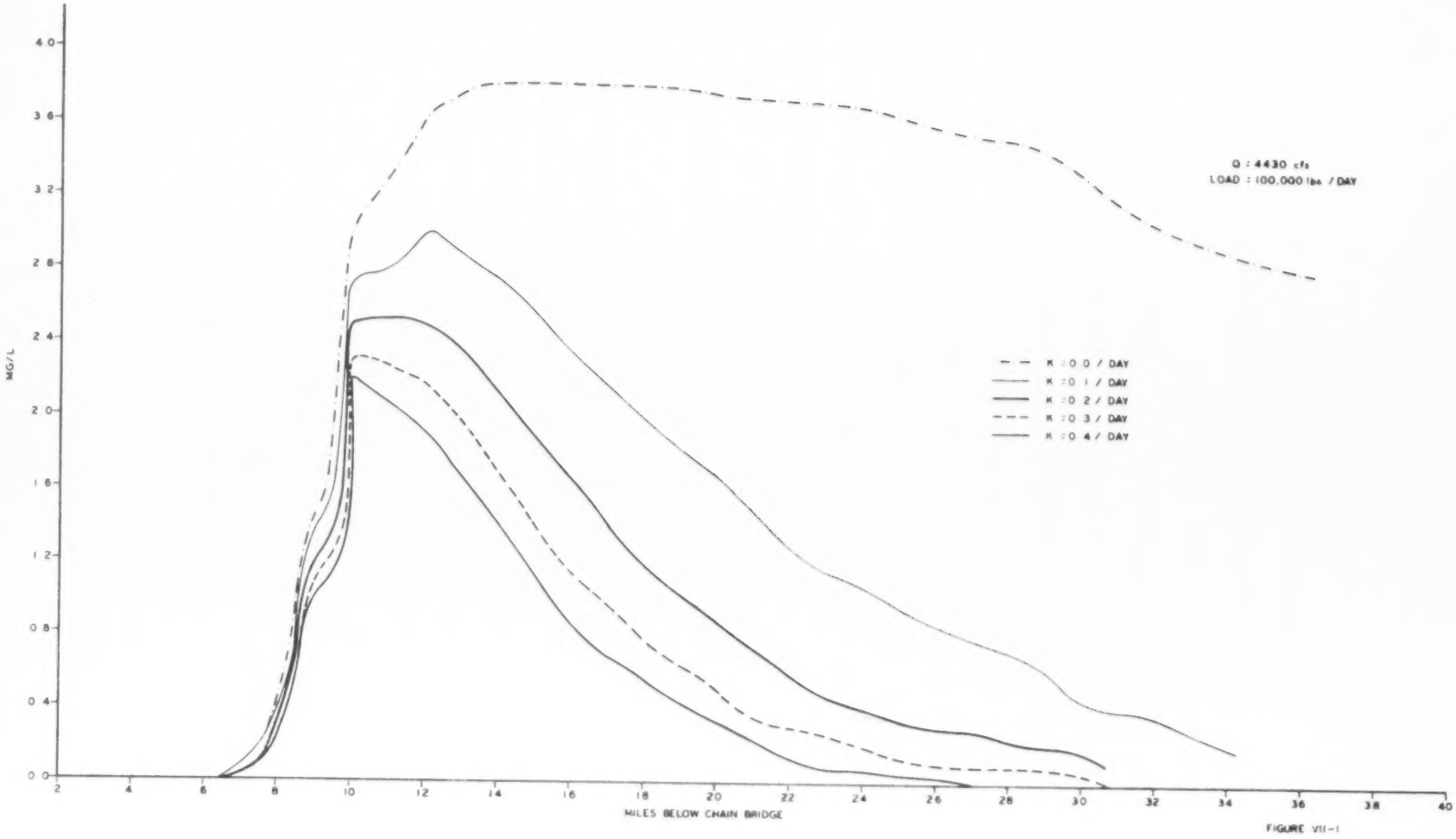



FIGURE VII-1

## EFFECTS OF DECAY RATES
THOMANN MODEL

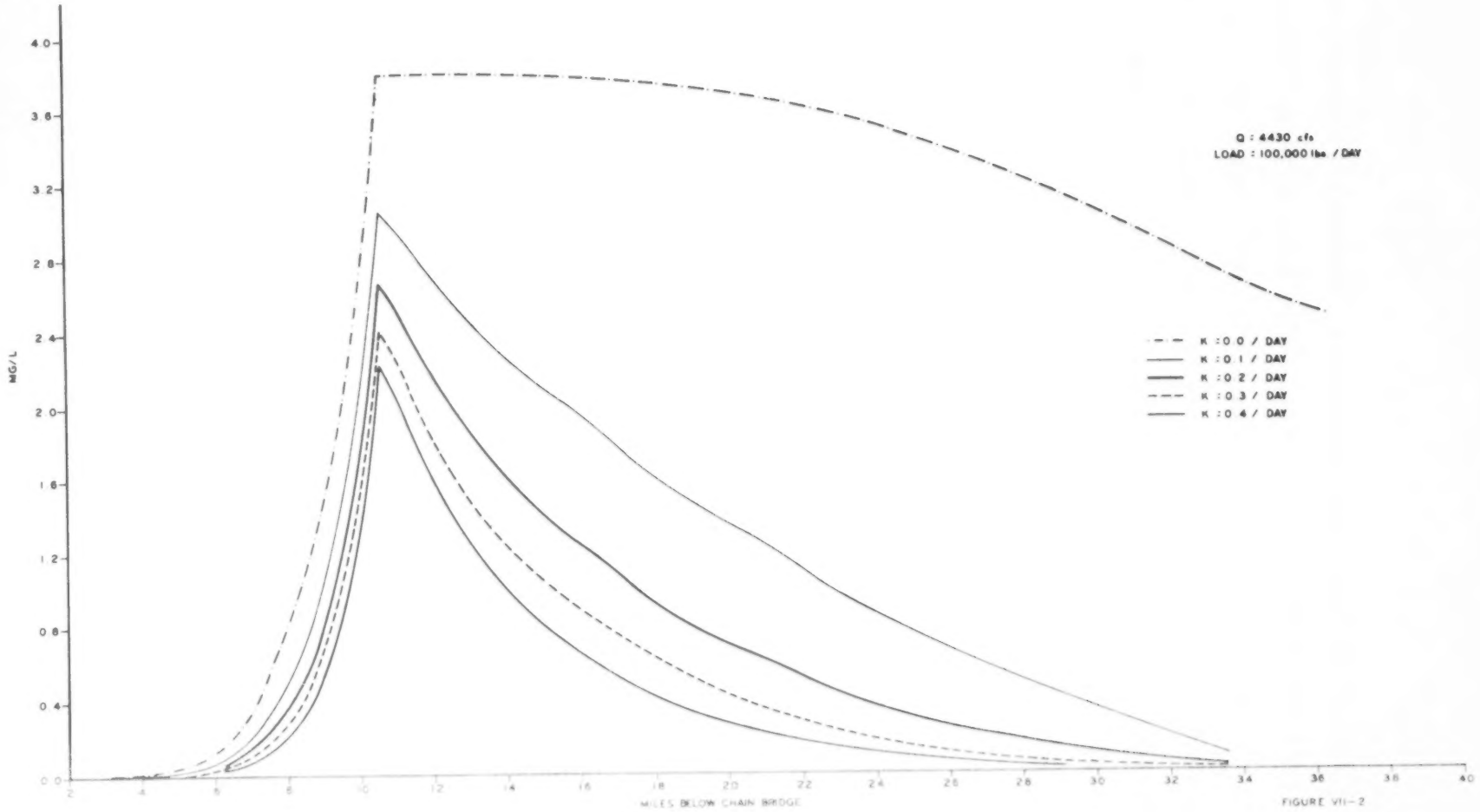



FIGURE VII-2

for each of the decay rates investigated. Moreover, the general shape and position of the profiles did not differ appreciably over this complete range in decay rates, indicating that either model can be used to simulate a given constituent regardless of its decay rate. As was noted previously when simulating dye data, the major difference between the two models' predictions was the pronounced peaking with the Thomann Model whereas the DEM "smoothed" the gradients considerably in the area of maximum concentration.

B. SEGMENT LENGTH

1. Thomann Model

A certain degree of refinement in the segmentation and the associated physical data of an estuary is necessary; however, the CTSL studies in the Potomac using the Thomann Model suggest that overrefinement of the geometry may be a wasted effort. Figures VII-3, VII-4, and VII-5 show simulated 1969 dye data for two separate networks that were applied to the Potomac Estuary. According to these figures, there is relatively low model sensitivity to the length of segments. The original 28-segment system, from which 15 segments were used for this analysis, produced basically the same profiles as the expanded system for 3 different days during the dye study period. The only differences noted were (1) slightly higher peak concentrations, and (2) slight downstream displacement of entire profile. The foregoing results remain true for decay rates of either 0.03 or 0.3 per day.

The effects of "induced dispersion" due to averaging concentrations throughout the larger volumes and longer distances in a coarse network appeared to be minimal.

2. Dynamic Estuary Model

A detailed investigation was not undertaken to determine the sensitivity of the Dynamic Estuary Model to network detail. In fact, the 114-node network used for all DEM simulations throughout this report was initially laid out for the Thomann Model. In order to avoid the time-consuming task of developing the additional data required for a new

network, the original segmentation, except for embayments, was used without basic change in the DEM. Subsequent simulations have indicated that this degree of refinement was adequate to reproduce the hydrodynamic and quality behavior in the prototype. A single run based upon a 28-node network, also specifically designed for the Thomann Model, showed that a network with this coarse detail could not accurately simulate tidal movement in the Potomac Estuary.

## EFFECTS OF SEGMENTATION

THOMANN MODEL DYE SIMULATIONS

NOVEMBER 6,1969

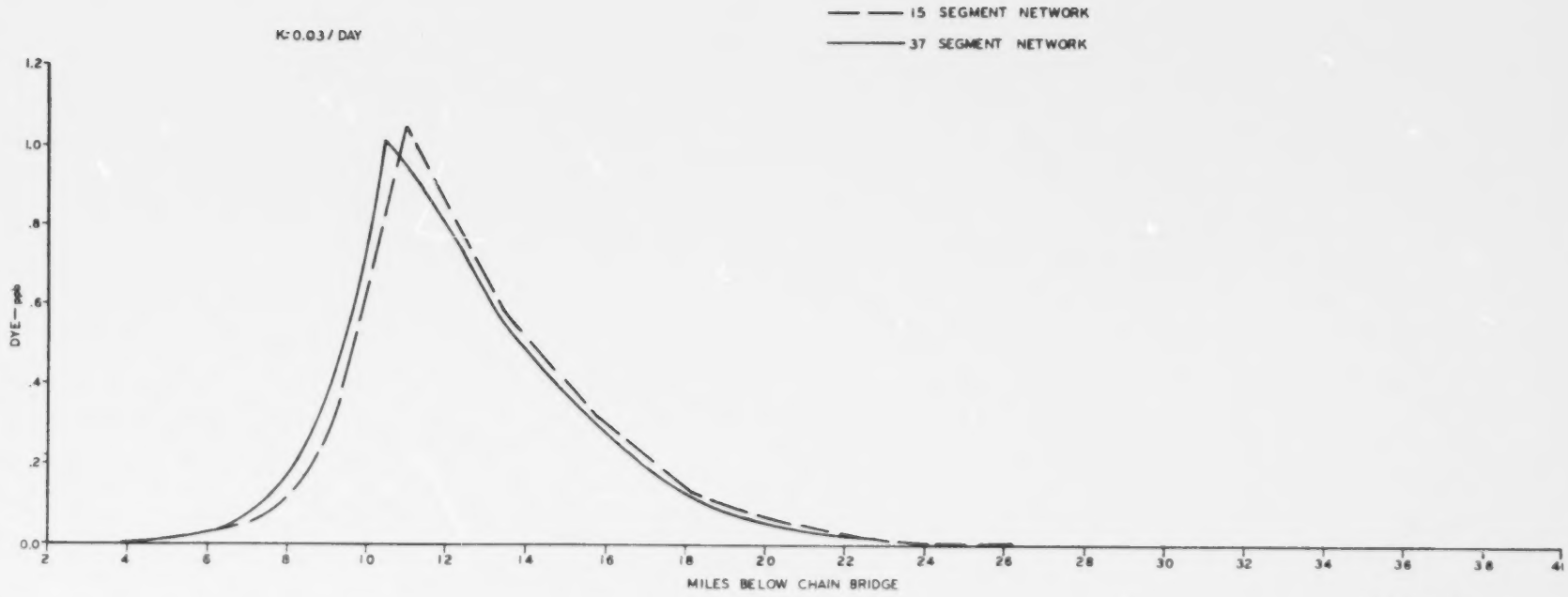



FIGURE VII—3

## EFFECTS OF SEGMENTATION

THOMANN MODEL DYE SIMULATIONS

NOVEMBER 12, 1969

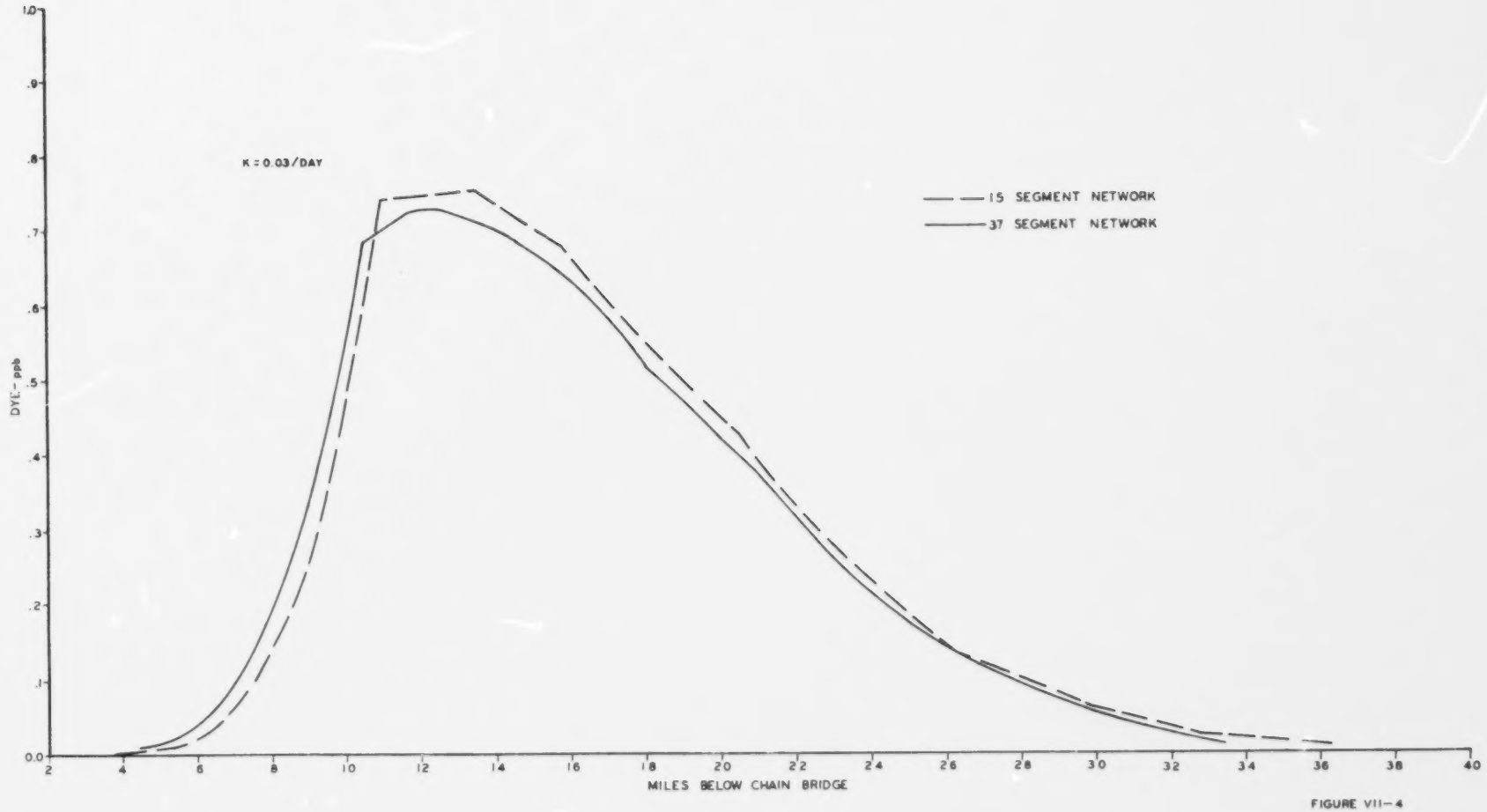



FIGURE VII-4

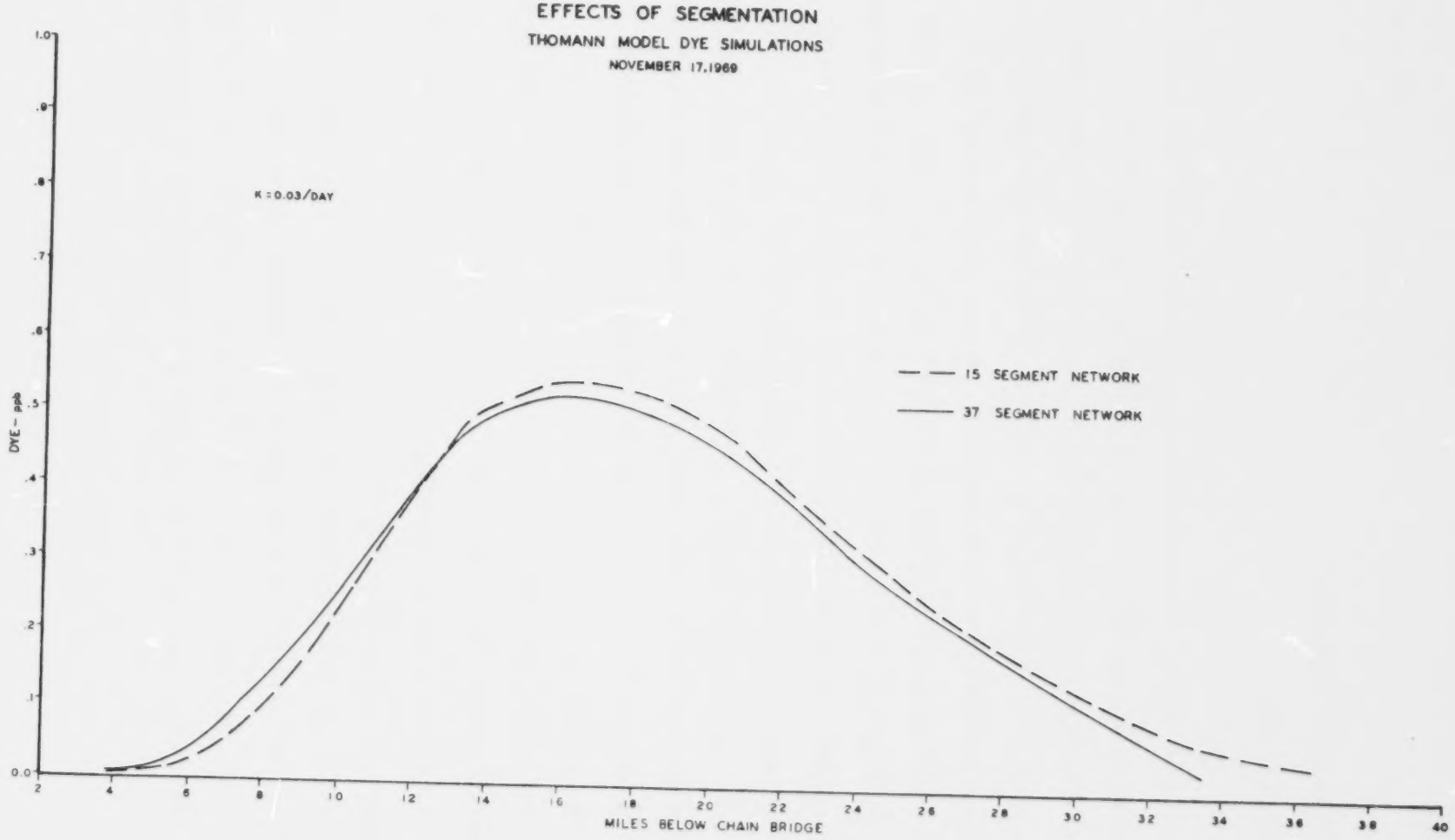

EFFECTS OF SEGMENTATION
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 17,1969
K = 0.03/DAY
15 SEGMENT NETWORK
37 SEGMENT NETWORK
DYE - ppb
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE VII-5

C. DISPERSION COEFFICIENT

1. Thomann Model

a. Point Discharges

Of the various input parameters investigated, the Thomann Model appeared to be most sensitive to the dispersion coefficient (K), especially when simulating constituents having low decay rates. The importance of this term is evident from an examination of Figure VII-6, VII-7, and VII-8 wherein simulated 1969 dye profiles are shown for K values ranging from 0.5 $mi^2$/day to 10.0 $mi^2$/day for all segments. The higher dispersion coefficients indicated greater upstream and downstream dye movement. Moreover, higher coefficients greatly decreased concentration peaks to compensate for the additional mass of dye at the leading and trailing edges. On November 17 (Figure VII-8), for example, dye peaks of 0.8 ppb, 0.7 ppb, 0.5 ppb, and 0.4 ppb were predicted for dispersion coefficients of 0.5, 2.0, 5.0, and 10.0 respectively. The remaining 2 days of the study for which data were plotted indicated similar results.

The spatial position of peak concentrations was also affected by the dispersion coefficient. As can be seen in Figures VII-7 and VII-8, increased dispersion coefficients resulted in a lower rate of downstream movement of the concentration peak.

The range in dispersion coefficients selected for this sensitivity analysis may have been extreme, but it nevertheless showed that a relatively accurate estimate of the dispersion coefficient was required for the Thomann Model either by conducting a dye study or by using some

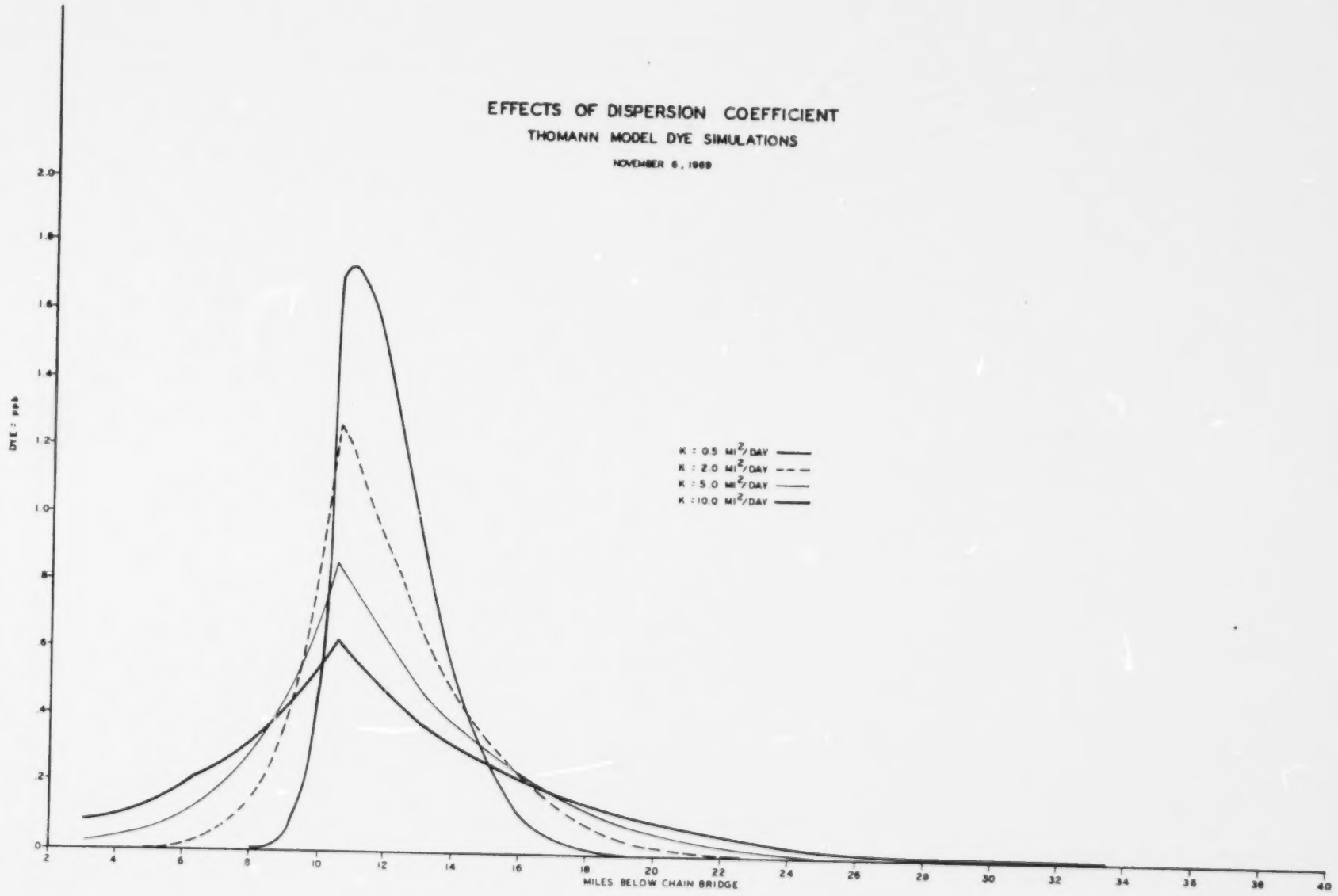

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 6, 1969
DYE : ppb
K : 0.5 MI²/DAY
K : 2.0 MI²/DAY
K : 5.0 MI²/DAY
K : 10.0 MI²/DAY
MILES BELOW CHAIN BRIDGE

FIGURE VII—6

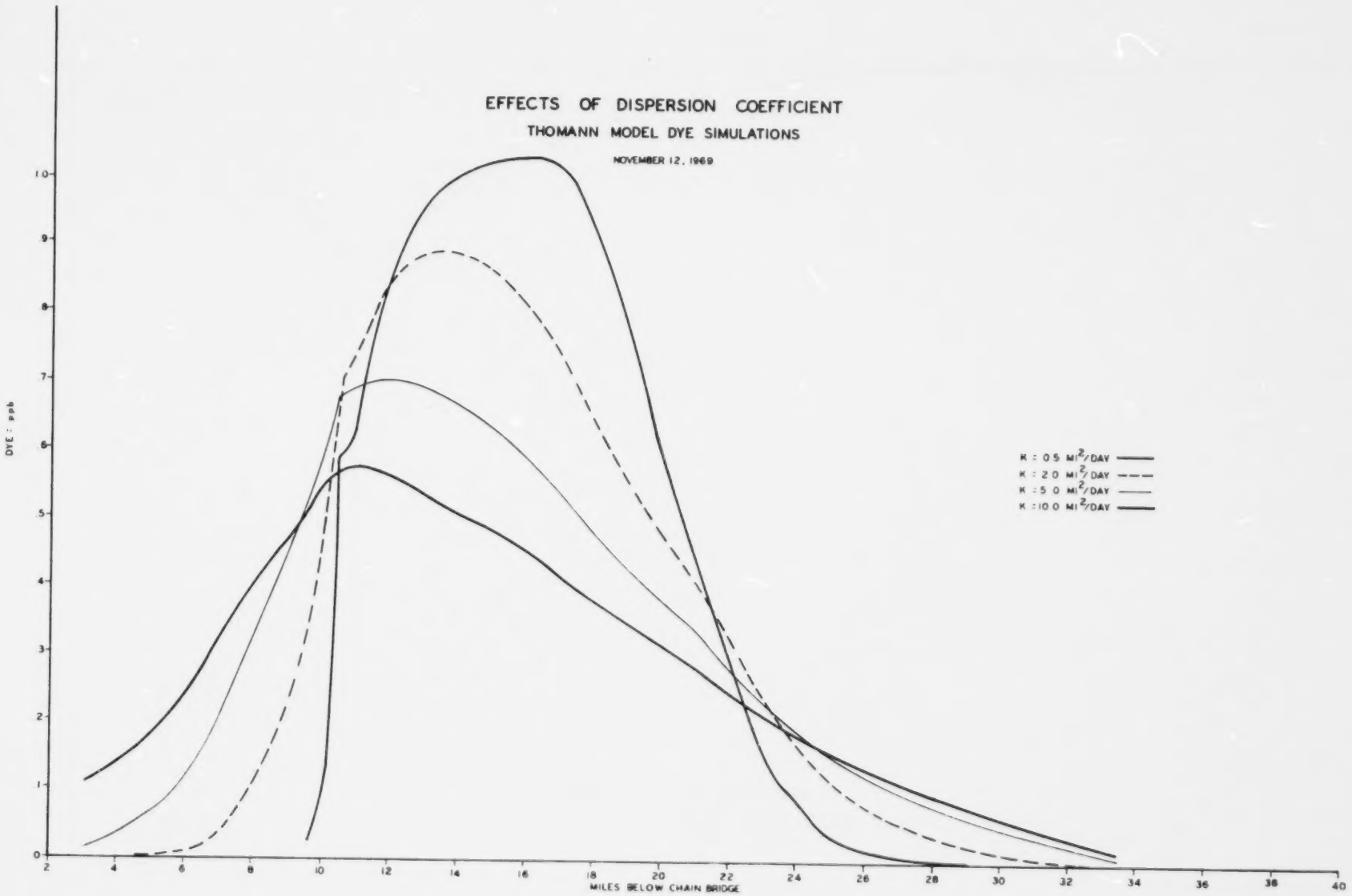

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 12, 1969
DYE : ppb
MILES BELOW CHAIN BRIDGE
K = 0.5 MI²/DAY
K = 2.0 MI²/DAY
K = 5.0 MI²/DAY
K = 10.0 MI²/DAY

FIGURE VII – 7

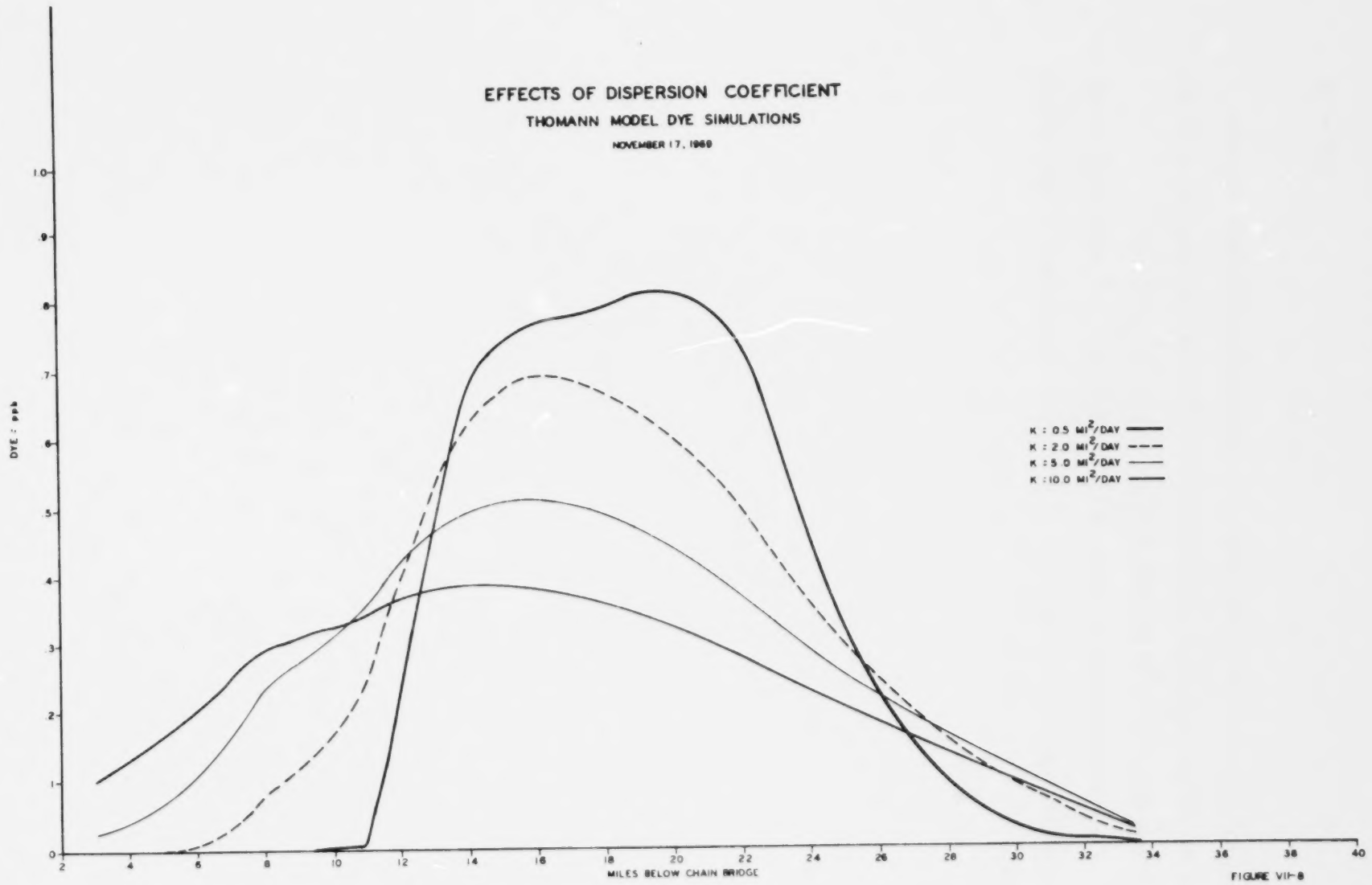

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 17, 1969
DYE : ppb
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE
K : 0.5 MI²/DAY
K : 2.0 MI²/DAY
K : 5.0 MI²/DAY
K : 10.0 MI²/DAY

FIGURE VII-8

natural tracer. The relationship of dispersion coefficient to fresh-water inflow, salinity, and possibly the physical characteristics of the system should also be defined prior to extensive model use.

For nonconservative constituents such as BOD, the effects of decay somewhat overcome the influence of dispersion coefficient in the Thomann Model.

b. Chloride Distributions

The effects of using three different sets of dispersion coefficients in the Thomann Model to simulate the annual (1969) chloride distribution at Nanjemoy Creek are shown in Figure VII-9. Increasing the previously verified dispersion coefficients of 2.0 to 16.0 $mi^2$/day by an order of magnitude resulted in a profound change in chloride concentrations. Instead of the model predicting chloride concentrations between 3,000 and 5,000 mg/l, which were comparable to observed values, the chloride levels were generally in the range of 7,000 to 9,000 mg/l. Similar differences could be expected at most other locations along the Potomac Estuary.

The third profile shown in Figure VII-9, based on a constant dispersion coefficient of 2.0 $mi^2$/day, indicates the considerable effect that changing chloride gradients exert on Thomann Model simulation studies. Under this assumption, a minimal amount of chlorides (< 500 mg/l) were transported up the Potomac Estuary from Chesapeake Bay. It can be concluded that the Thomann Model's sensitivity to dispersion is at least equally as great for simulating chlorides as it is for point-source discharges.

The relationship of dispersion coefficient and chloride concentrations established from Thomann Model simulations and actual data collected in 1969 during a relatively steady-state flow period (3,000 cfs-5,000 cfs) can be seen in Figure VII-10.

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL CHLORIDE SIMULATIONS
POTOMAC ESTUARY AT NANJEMOY CREEK

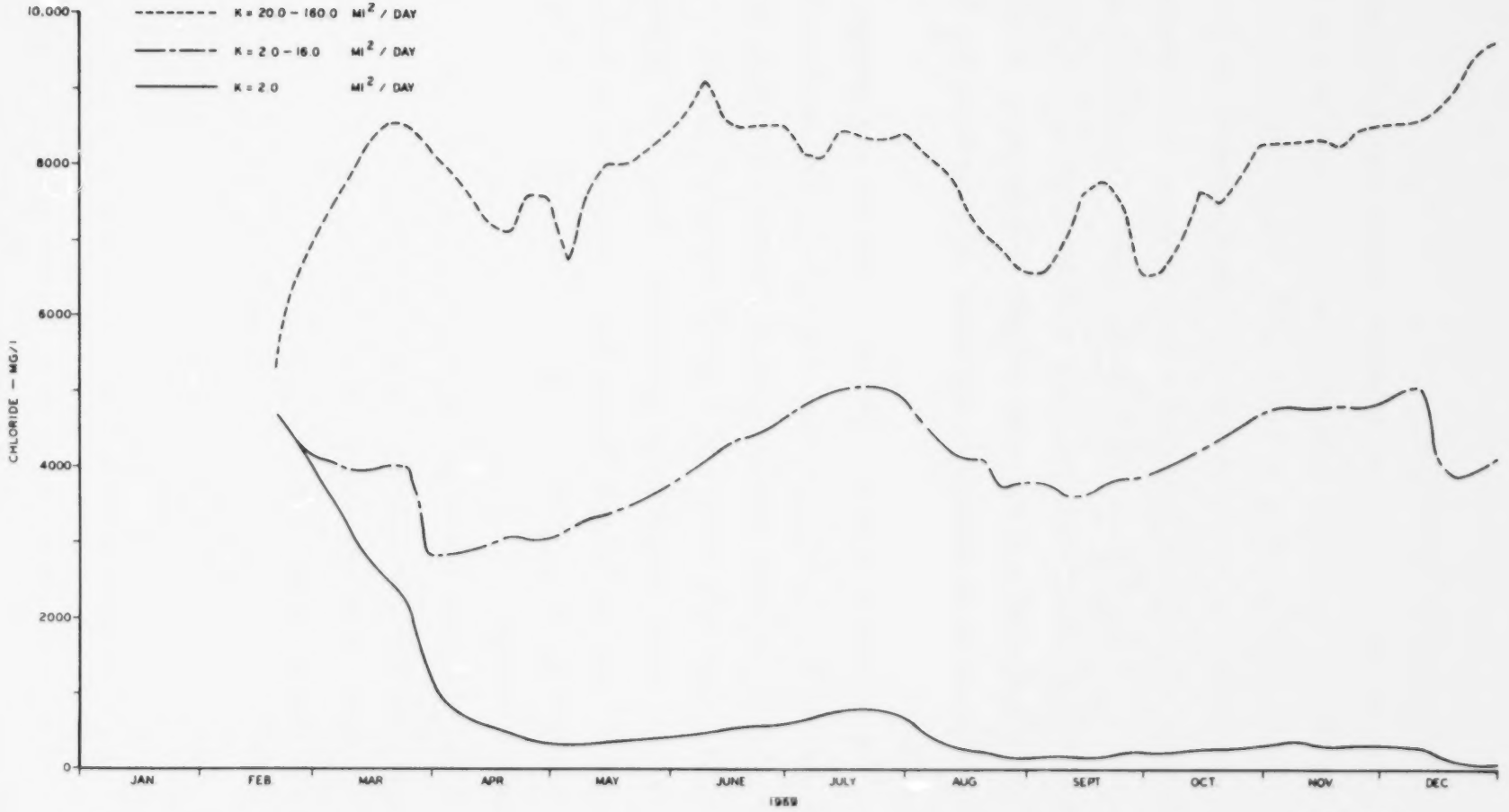



FIGURE VII – 9

## RELATIONSHIP OF DISPERSION COEFFICIENT TO CHLORIDES

### BASED UPON 1969 (3000 — 5000 cfs) DATA

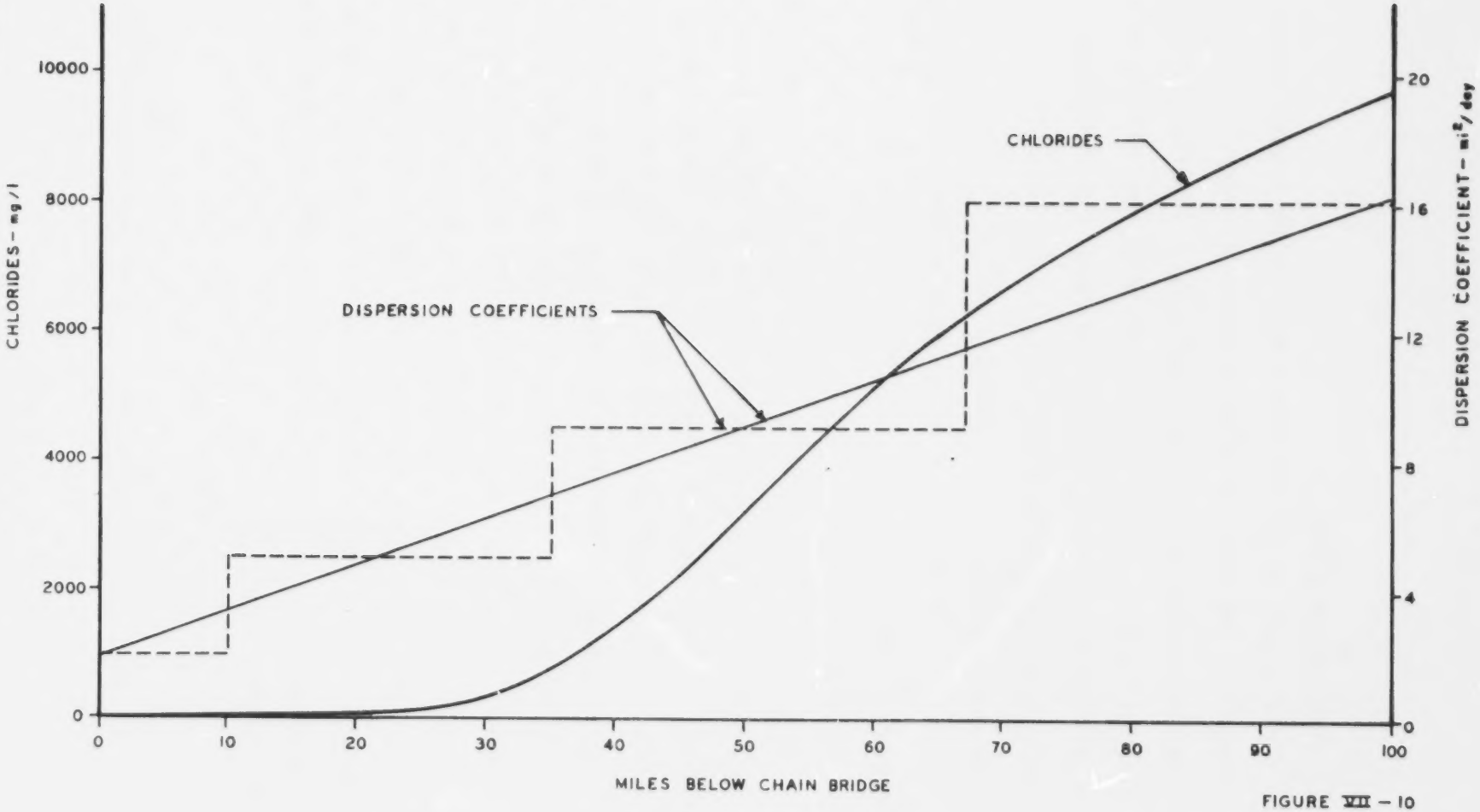



FIGURE VII – 10

2. Dynamic Estuary Model

Studies with the Dynamic Estuary Model in the Potomac Estuary indicate that the quality solution is relatively insensitive to the dispersion constant ($C_4$) when considering point discharges in the freshwater portion of the system. On the other hand, the simulation of salinity intrusion with this model indicated a significantly greater sensitivity to the dispersion term. The difficulty encountered with proper assignment of the dispersion term in high salinity areas is due in part to representing a vertically stratified system with a one-dimensional model.

a. Point Discharges

The effect of the dispersion constant, $C_4$, on the steady-state distribution resulting from a point discharge of 100,000 lbs/day at Blue Plains is indicated in Figure VII-11. These studies were conducted with a 4,430 cfs freshwater inflow and mean tidal conditions. As would be expected, increasing the dispersion constant generally lowers the peak concentration and reduces the concentration gradient somewhat. These comparisons indicate that the predicted distribution resulting from a point discharge is relatively insensitive to the dispersion term in the Dynamic Estuary Model. Because this model simulates advective transfers and mixing resulting from tidal action, there is significantly less dependence on a dispersion term than that shown with the Thomann Model.

EFFECTS OF DISPERSION CONSTANT($C_4$)

ON DYNAMIC ESTUARY MODEL SIMULATIONS

FOR A POINT DISCHARGE

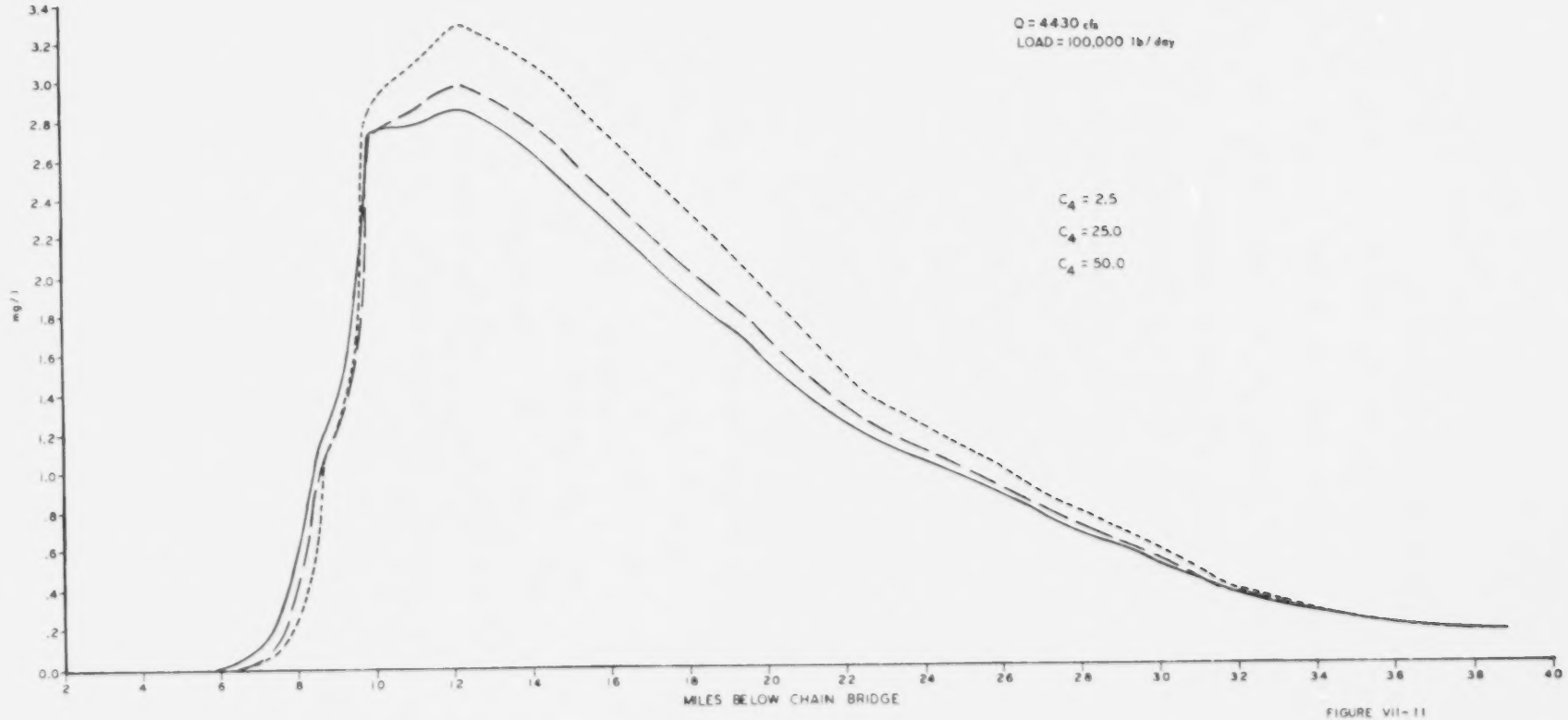



FIGURE VII-11

b. Chloride Distributions

As a second test of the significance of the dispersion term $C_4$ in the Dynamic Estuary Model, an attempt was made, as discussed in the preceding chapter, to simulate changing salinity conditions in the Potomac Estuary during the July 1965 to December 1965 period.

The profiles representing prototype conditions for July 7-8, 1965, and December 1-2, 1965, are shown in Figure VII-12. The initial simulation was completed with the dispersion constant $C_4$ equal to 2.5 for the entire system (labeled model prediction number 1 in Figure VII-12). A second simulation with $C_4$ increased to 25.0 (model prediction number 2 in Figure VII-12) resulted in only a slightly better agreement. From these two simulations, it was apparent that the model was significantly misrepresenting the rate of chloride incursion as well as the chloride distribution through the system. The discrepancies could be attributable to any of several causes, including:

1) Network layout - a brief discussion of the effect of network layout on model predictions is presented in other sections of this report. No further attempt to determine the effect of the network layout on chloride intrusion was made. It remains as a possible significant cause of the poor simulation agreements.
2) Prototype data - insufficient and/or inadequate data to establish prototype behavior can present appreciable problems in model verification. For this comparison, however, the data

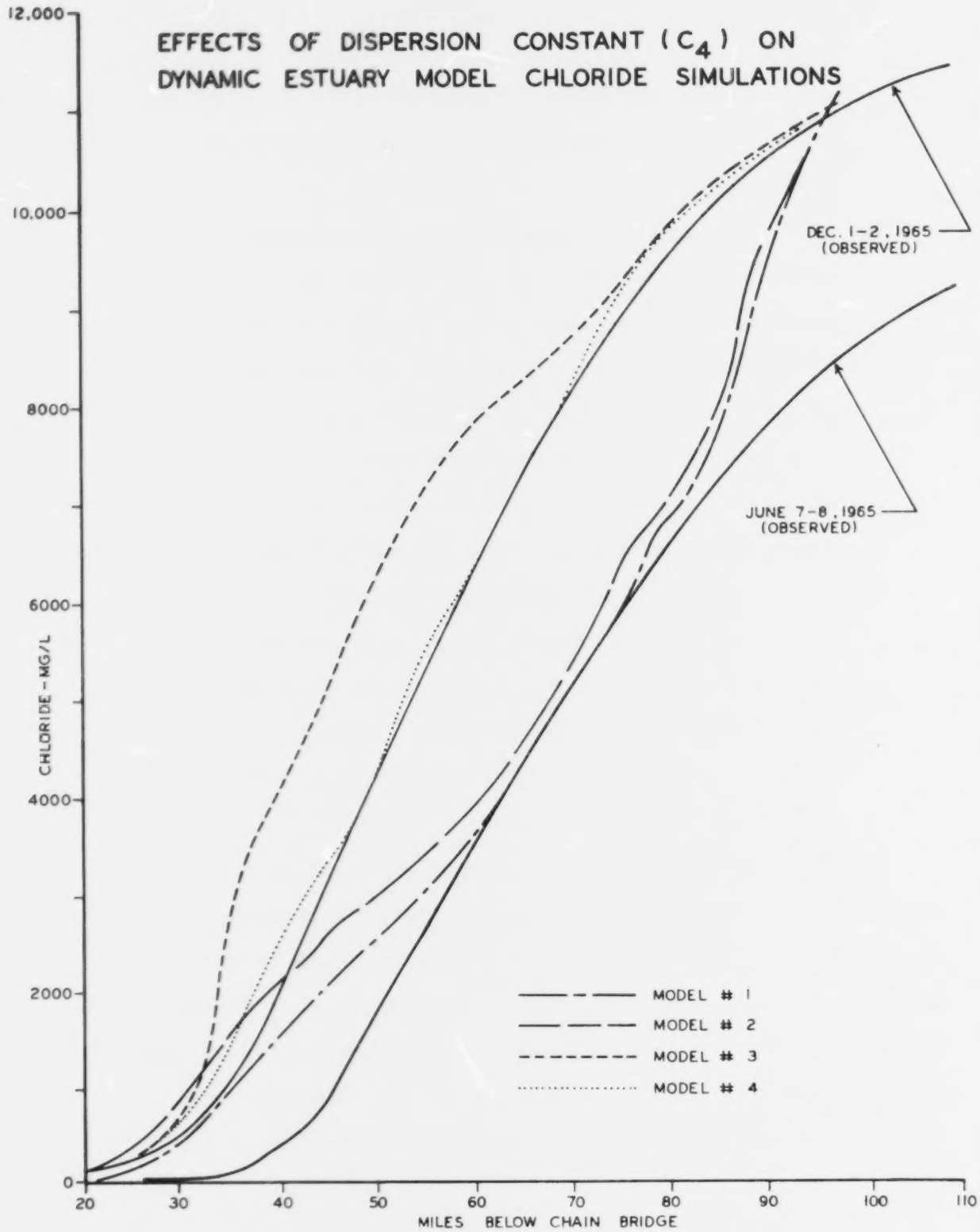



FIGURE VII-12

were considered sufficient to adequately define the profiles and to dismiss the prototype data as a major cause of the discrepancies.

3) Advective transport techniques - the techniques utilized for advective transport within the quality model can significantly affect the rate of movement and the profile of any quality constituent but particularly one which has steep concentration gradients such as salinity. This "numerical mixing" phenomenon is discussed in detail in the DEM Documentation Report [8].

4) Dispersion - although previous applications [3] of the Dynamic Estuary Model indicated that transport due to dispersion was relatively insignificant when compared to advective transport, recent studies by Harleman [7] demonstrated that the dispersion term can be very important in those portions of an estuary with vertical or longitudinal concentration gradients. For this reason the sensitivity of the dispersion term on model predictions was further investigated.

The studies by Harleman [7] indicate that dispersion in areas with perceptible salinity gradients is many times greater than dispersion in areas with uniform salinity. To evaluate the significance of this phenomenon in the Dynamic Estuary Model, it was necessary to incorporate the ability to vary the constant $C_4$ with distance from the seaward boundary. For this study, the estuary was divided into three zones with a different constant for each. The $C_4$ constant was assigned a relatively

low value in both the upstream and middle reaches but was increased substantially in the seaward reach. In one simulation (labeled model number 3 in Figure VII-12) $C_4$ was assigned a value of 2.5 in the upper 40 miles of the estuary, 25.0 in the next 20 miles, and a value of 250.0 between River Miles 60 to 96 (the seaward boundary for the model). This simulation demonstrated the marked effect of increasing the dispersion term. The final simulation presented (model number 4 in Figure VII-12) was a result of utilizing a $C_4$ value of 15.0 in the upper 55 miles of the estuary, 80.0 in the next 15 miles, and 250.0 in the downstream 29 miles (River Miles 70-99). Further refinement and adjustment of these dispersion terms undoubtedly would have resulted in even more favorable agreement between model and prototype behavior. However, because of uncertainties in the prototype data base, the uncertainty of the model network effect and other factors, further refinement in this one aspect of the model did not appear warranted. The conclusion reached from this study was that a significant transfer of chloride across the seaward boundary above and beyond that entering the model via the advective transport mechanism is necessary to adequately simulate chloride distributions in the Potomac. This was demonstrated in this study by substantially increasing the dispersion term in the downstream portions of the estuary. Thus the dispersion term appears to be the important factor in predicting the distribution and rate of transfer of a water quality constituent having the ocean as its major source such as chlorides. It should be kept in mind that no specific study was

conducted to determine the effect of the network layout on the rate of advective transfer across the seaward boundary. Whether or not this is a significant factor in the case of the Potomac system has yet to be demonstrated.

It is also possible that the dispersion constants determined in this analysis are applicable only for the flow and tidal conditions existing at the time. No specific analysis was conducted to determine whether these constants are appropriate for other freshwater flow conditions.

## D. ADVECTIVE TRANSPORT

### 1. Thomann Model

As mentioned previouslv, the advective proportionality factor ($\alpha$) should theoretically range between 0.5 and 1.0 depending on the relative importance of dispersion and advection for a given estuary. In the Thomann Model, it is computed as a function of the eddy exchange coefficient and flow. Simulated dye profiles based upon $\alpha$ values of 0.5, 0.75, and 1.0 for all model segments with other variables held constant are shown in Figures VII-13 and VII-14. As can be seen in both of these figures, the three profiles almost coincide indicating that the model is quite insensitive to $\alpha$. Decreasing $\alpha$ results in slightly higher peak concentrations accompanied by less upstream movement. The configuration of the profile's leading edge is unaffected.

In addition to dye simulations, the effects of $\alpha$ on chloride modeling was also investigated. The considerably higher concentration gradient found in the longitudinal chloride distribution did not appear to increase the Thomann Model's sensitivity to the advective component of mass transport as was noted with the dispersion component for similar conditions.

Based upon the above discussion, it would seem that the advective transport mechanism plays an insignificant role in the Thomann Model.

EFFECTS OF ADVECTION FACTOR ($\alpha$)
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 6, 1969

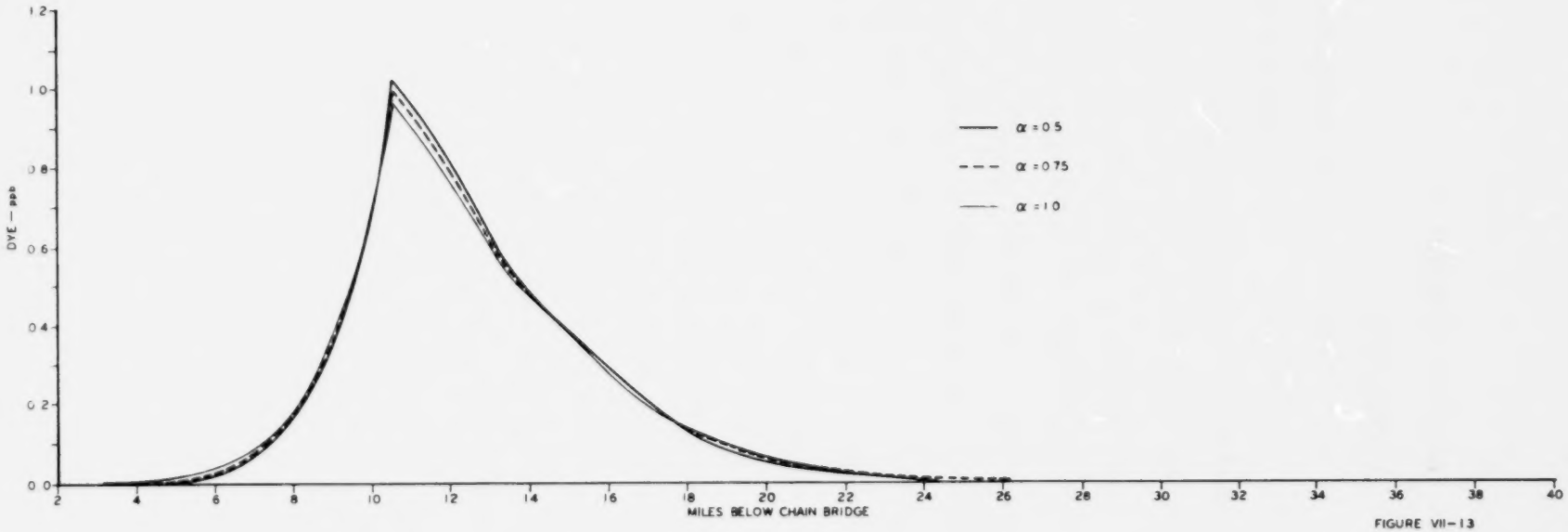



FIGURE VII-13

EFFECTS OF ADVECTION FACTOR ($\alpha$)
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 12, 1969

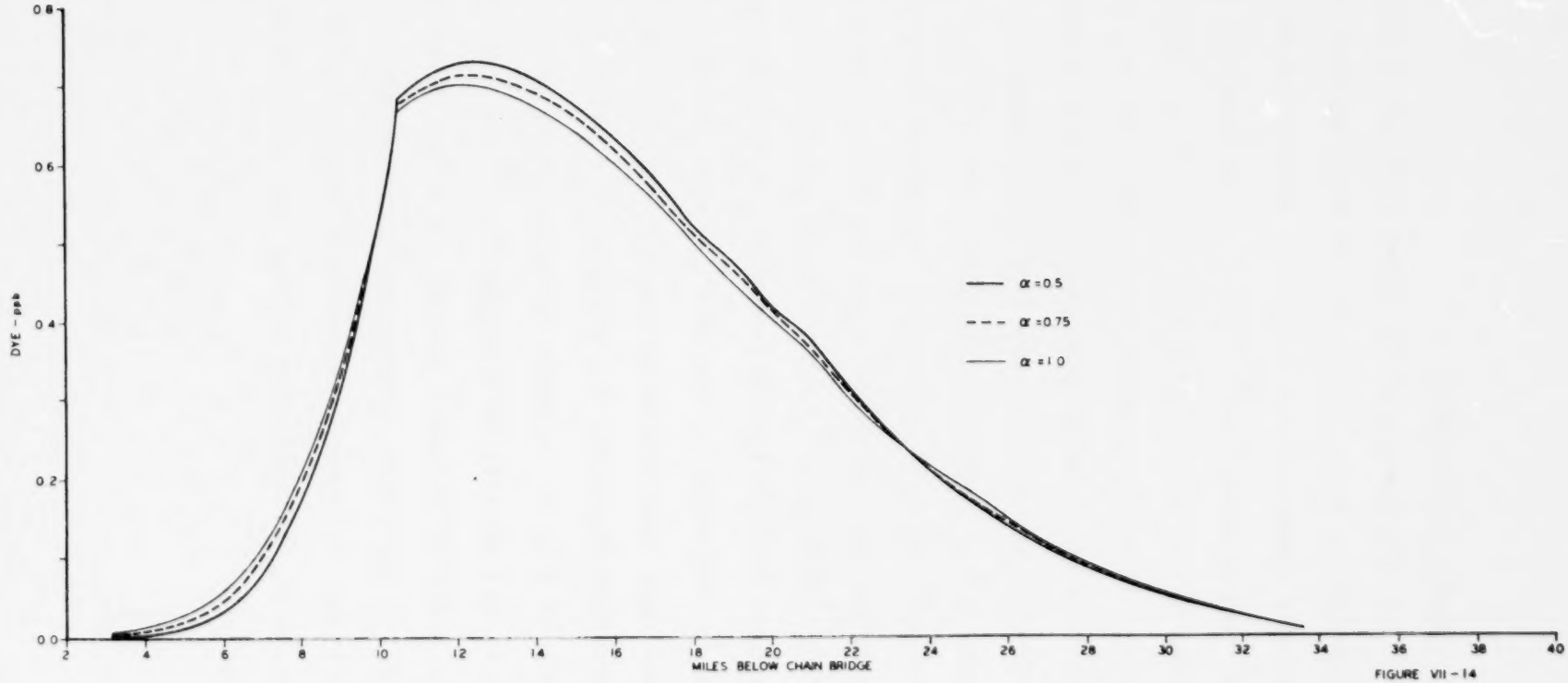



FIGURE VII - 14

## 2. Dynamic Estuary Model

The effectiveness of the method utilized for advective transport determination in the Dynamic Estuary Model was demonstrated by simulating a somewhat shorter historical salinity incursion period than that utilized to demonstrate the effect of the dispersion term. For this analysis, the chloride conditions in the Potomac during the period October 19 through December 2, 1965, were used as a basis for comparing two different solution techniques. The effect of changing the concentration in the advected water from that computed at a channel's quarter point to that computed at the upstream third point is illustrated in Figure VII-15. As can be noted, the quarter-point method significantly increases the predicted upstream incursion and tends to flatten the gradient more than the third-point method. While the third-point method produces the more favorable comparison with prototype behavior, it should not be interpreted as the "best" the model can do since the comparisons could have been improved by use of appropriate dispersion constants throughout the estuary (as discussed in a previous section). The curves are included only to illustrate the effect of the advective solution technique. It is apparent that the model predictions are sensitive to the method used for advective transport; however, the effect is more pronounced for water quality constituents with substantial concentration gradients such as chloride. For other water quality constituents with less significant gradients, the predictions are much less sensitive to the solution technique used.

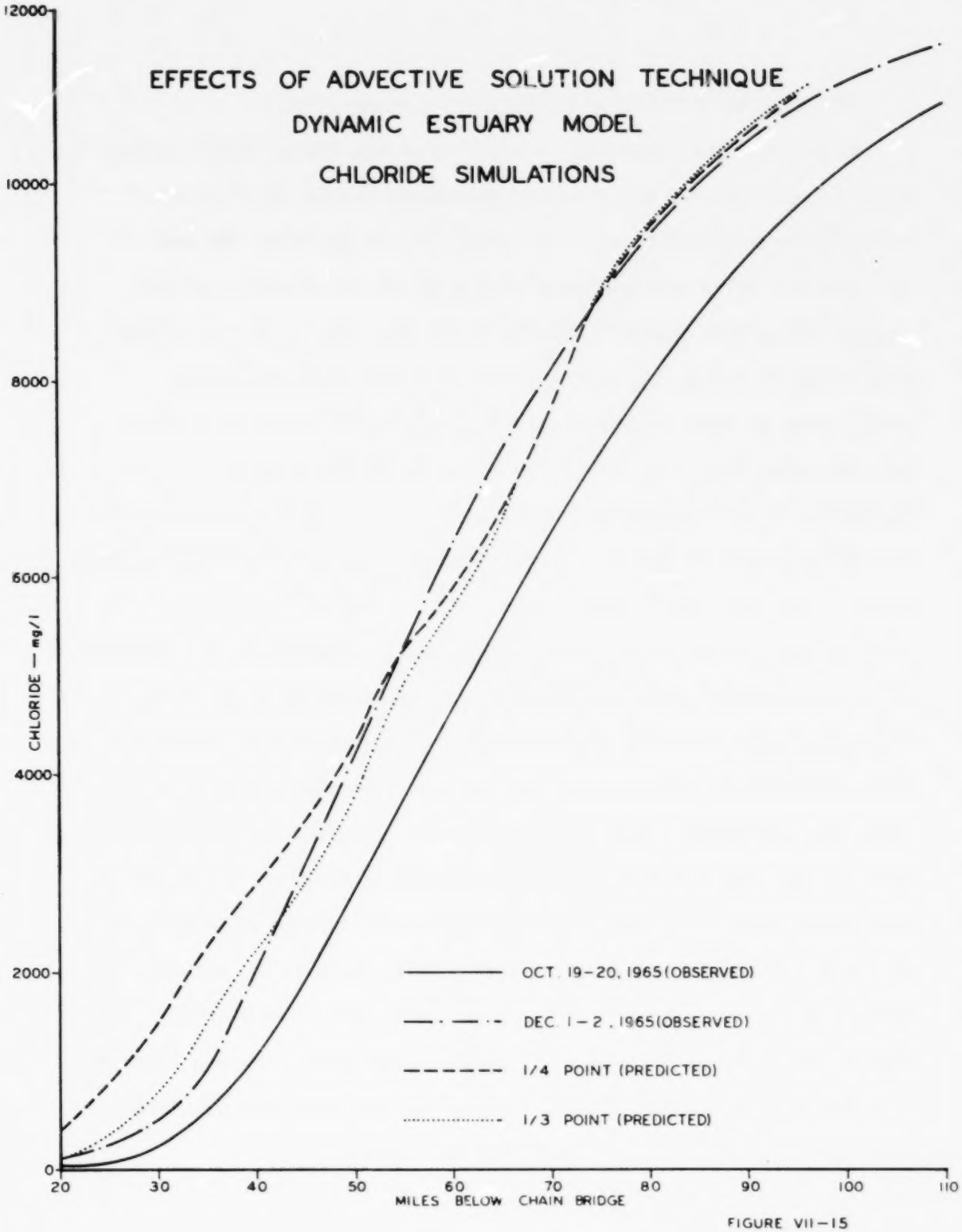



FIGURE VII-15

E. RIVER FLOW AND DISPERSION COEFFICIENTS (THOMANN MODEL)

To increase the predictive reliability of the Thomann Model in the upper Potomac Estuary, the effect of freshwater inflows on dispersion coefficients was investigated. The simulation of November 1969 and June 1965 dye study data indicated that a direct relationship existed whenever flows were between 1,400 and 4,000 cfs. The increased inflows which occurred during the study periods required higher dispersion coefficients in order to obtain a satisfactory agreement between prototype and model data. Moreover, a study in the Delaware Estuary by Paulson [9] also indicated that dispersion increased directly with flow. This relationship may be partly due to the dissipation of the larger energy levels associated with greater flows.

The approach adopted for this analysis was a comparison of simulated data from the tidal and nontidal models for the upper 30 miles of the Potomac Estuary. The data generated by the "real-time" tidal model was used as a basis for determining when the most favorable predictions, hence most applicable dispersion coefficients, occurred with the Thomann Model. Four separate flow conditions, ranging from 930 cfs to 20,000 cfs, were investigated. For each inflow, an arbitrary loading at Blue Plains of 100,000 lbs/day with a decay rate of 0.1/day (base e) was assumed. Initial and boundary concentrations were set to zero in both models and simulations continued in time until steady-state conditions were observed.

The dispersion coefficients yielding the best data with the Thomann Model are plotted as a function of flow in Figure VII-16.

# DISPERSION COEFFICIENT VS. FLOW
## THOMANN MODEL
### UPPER POTOMAC ESTUARY

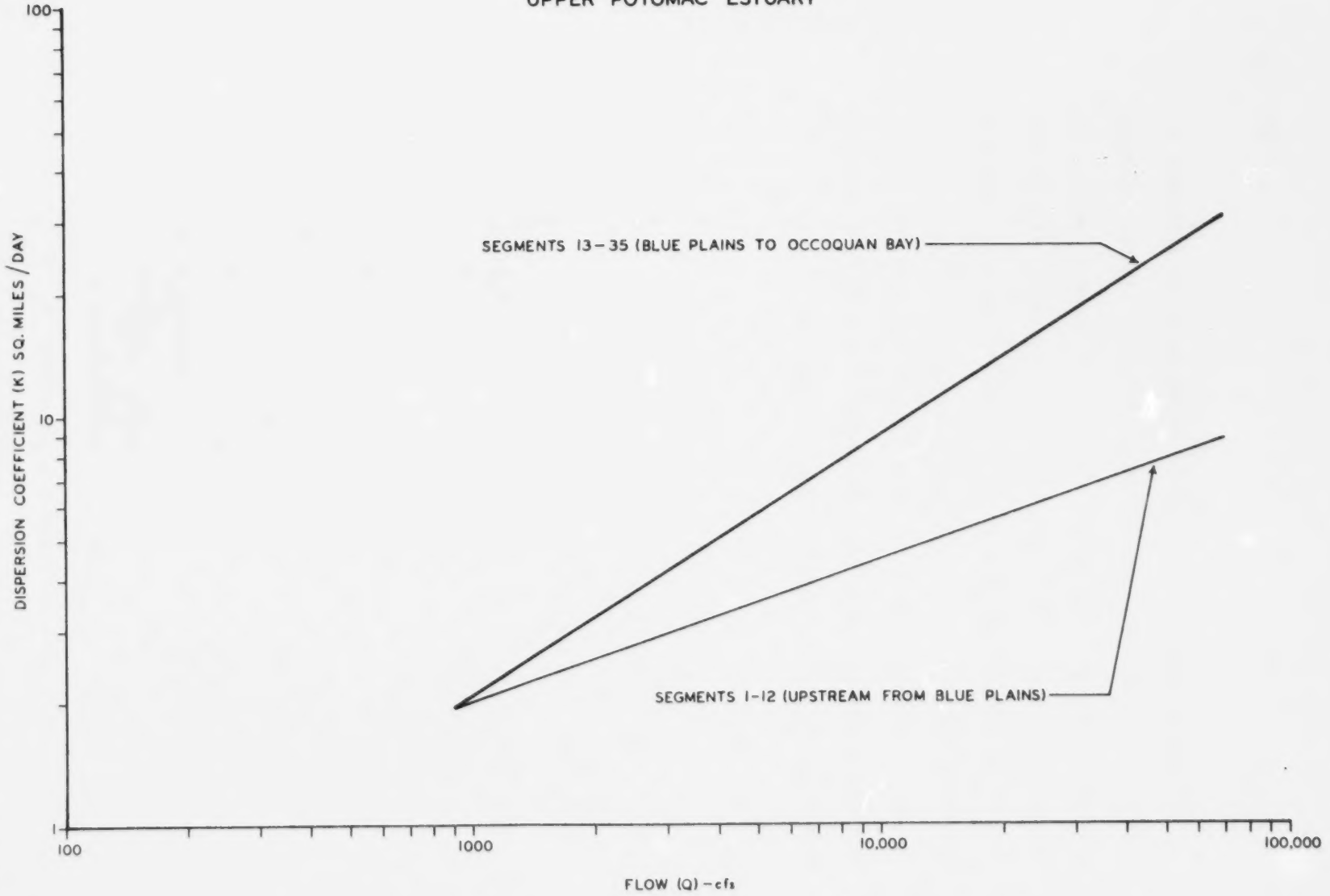



FIGURE VII - 16

As can be seen in Figure VII-16, there were two different K versus Q relationships--one applied to the model segments upstream from the discharge point and the other to the segments between the discharge point and the Occoquan Bay. The effects of flow on the dispersion coefficient were more pronounced in the downstream direction but nevertheless a direct relationship between the two existed upstream as well. For the higher flow conditions, it appeared that the increased downstream advective movement overshadowed the effects of upstream dispersion resulting from the higher coefficients.

F. MANNING COEFFICIENT AND TIDAL EFFECTS (DYNAMIC ESTUARY MODEL)

Studies were made with the Dynamic Estuary Model to ascertain the effects of Manning's roughness coefficient (n) on the steady-state hydraulic solution and its subsequent effects on the quality program. Moreover, two different tidal conditions (mean annual and mean spring tide) were simulated hydraulically to determine the sensitivity of tidal input on quality predictions.

The following table contains various sets of Manning coefficients for the main Potomac and the corresponding dynamic steady-state tides predicted at Washington. For purposes of comparison, the mean tide which was used for this investigation had an average range at Washington of 2.9 feet and phasing differences referenced to Piney Point of 6.4 hours and 7.1 hours for high and low water, respectively. At Piney Point, the average tidal range was 1.4 feet.

Table VII-1

Effects of Manning Coefficients on Tides

| "n" (decreasing downstream) | Tidal Range (ft.) | High and Low Lag Times (hrs.) |
|---|---|---|
| .023 - .020 - .016 | 2.60 | 5.80 - 7.00 |
| .020 - .019 | 2.23 | 6.05 - 7.10 |
| .025 - .020 - .017 | 2.48 | 5.80 - 7.00 |
| .025 - .022 - .020 | 2.13 | 6.10 - 7.15 |
| .020 - .017 - .015 | 2.73 | 5.85 - 7.00 |
| .020 - .017 - .014 | 2.85 | 5.90 - 7.00 |

It is evident from the above data that tidal range was more sensitive to channel roughness than tidal phase. The greater roughness values slowed the tidal movement and thereby produced greater lag times and lower ranges. The best agreement was obtained with "n" ranging from .020 to .014. While the hydraulics were relatively sensitive to Manning coefficients, quality program output based upon two different sets of coefficients indicated that simulated concentrations were essentially unchanged. An attempt to overrefine Manning coefficients does not appear warranted from the standpoint of required predictive capability.

In addition to the use of mean tidal figures previously discussed, numerous simulation studies were made for the Potomac using the mean spring tidal figures. This particular tide has a range of 1.6 feet at Piney Point and 3.3 feet at Washington. The most favorable simulation of the spring tide again occurred with Manning coefficients varying from .020 to .014. The predicted quality data in the upper Potomac Estuary resulting from the use of mean spring tidal figures did not differ appreciably from a mean annual tide hydraulic condition. Maximum concentration differences were less than 10 percent.

# CHAPTER VIII

# ENGINEERING CONSIDERATIONS

## A. DISPERSION AND ADVECTION

The mathematical model simulation studies discussed in this report indicated that dispersion coefficients were particularly significant when a "tidal-averaging" concept was used. Since lateral differences in tidal velocities are the predominant driving force in physical dispersion, a nontidal system must include a gross term approximating the total effect of various individual dispersion components.

The dispersion coefficient employed in the Thomann Model was hard to evaluate. Two large scale dye studies were conducted in the upper Potomac Estuary in an attempt to characterize dispersion, but the results appear to contain discrepancies. The 1969 dye study yielded dispersion coefficients of 2.0 and 3.0 $mi^2$/day for 1,900 cfs and 3.0 and 5.0 $mi^2$/day for 4,000 cfs. For a similar reach of the Potomac, values of 2.0 $mi^2$/day (3,200 cfs) and 1.0 $mi^2$/day (1,600 cfs) provided the best agreement between observed and simulated 1965 dye study data. While it can be concluded that dispersion coefficients in the Thomann Model for a point-source discharge appeared to be directly related to freshwater inflow rates, the probable magnitudes to be assigned for predictive studies using fairly conservative constituents are difficult to determine. It should be noted that the aforementioned dye studies produced only approximate values of dispersion which have limited application. When constituents exhibiting significant degradability are simulated, i.e., $K > 0.1$/day, the effects of

dispersion in the nontidal modeling approach will be decreased because the natural decay process dominates the effects of transport and primarily governs the constituent distribution.

Simulation of chloride data also created problems because dispersion coefficients appear to be greatly influenced by salinity gradients. The 1966 and 1969 chloride simulations, as presented in Chapter VI, again indicated wide variation in dispersion coefficients both spatially and temporally. From the dispersion standpoint, the 1966 chloride simulations yielded results comparable to those of the dye studies, i.e., dispersion coefficients were found to be directly proportional to freshwater inflow. However, the 1969 chloride simulations showed a different relationship. In order to realize basic agreement between simulated profiles and observed data, dispersion coefficients were held constant for the entire year of simulation regardless of freshwater inflow rates. Not only did this approach differ with the direct K versus Q relationship developed in Chapter VII for a point discharge but with the logical definition of dispersion as applied to chloride intrusion as well. It would appear that the true dispersion coefficients for a tracer discharged into the upper reaches of the Potomac Estuary and dispersing primarily in a downstream direction are directly proportional to inflow rates because advection and diffusion forces have accumulative effects. Dispersion coefficients for chlorides and other constituents dispersing upstream should then be inversely proportional to flow; although this was not reflected in the Thomann Model simulations presented

in this report. Since chloride intrusion is in an upstream direction and the forces of advection and diffusion oppose each other, it is reasonable to assume that during low-flow periods, maximum intrusion would result. To duplicate similar performance in the model, high dispersion coefficients were necessary to simulate the downstream movement of the chloride wedge.

Discrepancies in the interrelationship between dispersion, advection and flow on the hydrodynamic behavior and the relative insensitivity of the advective proportionality factor suggest that tidal and nontidal advection is deemphasized in the Thomann Model. The method by which this model handles incoming flows may be responsible for deficiencies in the basic transport mechanisms of dispersion and advection. A given flow sequence, for example, is assumed to occur instantaneously throughout the system, indicating that the hydraulics are strictly a function of velocity (Q/A) and not volume displacement. It can be concluded that continual refinement of the dispersion coefficient and a sound understanding of how it is affected by various factors within a given system are mandatory when applying the Thomann Model to any great extent.

The simulations for a point-source discharge conducted using the Dynamic Estuary Model indicated that a much more accurate representation of advection and dispersion can be expected. The insensitivity of this model to the dispersion component and the relative importance of tidal

and advective forces were indications that the DEM more realistically approximates the hydrodynamic behavior of the prototype.

In the case of chlorides or other constituents entering the Potomac Estuary from the Chesapeake Bay, caution must be exercised when assigning the dispersion term $C_4$ in areas with large concentration gradients. The chloride simulations performed with the DEM showed that dispersion can be directly related to the concentration gradient and furthermore that the advective concentration is quite important. Whether this can be attributed to the coarse network used or some other peculiarity in the solution technique has not been adequately determined. Since this model employs a "real-time" system, it is essential that the total quantity of constituent crossing the seaward boundary over a complete tidal cycle be accurately represented, even if this is done by drastically increasing dispersion.

B. MODEL COMPARISON

As discussed in previous sections of this report, the primary disadvantage of the Thomann Model, or any other nontidal model, is the difficulty in selection of appropriate dispersion coefficients. Costly dye studies and field data collection can provide an approximation of this coefficient but the accuracy necessary for various predictive water quality studies will probably remain to be developed. Other important disadvantages of the Thomann Model are its inability to (1) branch in a lateral direction, (2) link more than two constituents, and (3) simulate the effects of tides on the distribution of a constituent.

The major advantages of the Thomann Model over the FWQA Dynamic Estuary Model as presently programmed are (1) less stringent input requirements, (2) its ability through Namelist I/O option to change input variables, such as flow on a daily basis, and thereby readily simulate an entire year's or season's characteristics, and (3) the capability of running several different data decks "back-to-back" without having to resubmit the whole program. In light of the above, one can investigate many more alternatives in much less time with the Thomann Model which is important when time is critical.

Except as noted earlier, the Dynamic Estuary Model does not appear to be very sensitive to the dispersion coefficient since tidal effects are included. Furthermore, the short time step which can be used in the real-time quality solution enables this model to make a better prediction for constituents having a relatively fast reaction rate. Nitrification

analysis, for example, may be better investigated with the Dynamic Estuary Model. Recent refinement in the quality program has added several additional source and sink terms in DO budget analyses. The effects of algal photosynthesis and respiration based upon conversion of inorganic nitrogen to chlorophyll a, nitrogenous oxygen demand, benthic oxygen demand, and modifications to the reaeration term have been programmed into the model and should definitely increase its capability in predicting DO concentrations in eutrophic estuarine waters. Another recent innovation was the expansion of the first-order reaction system to any order system. This was the outcome of preliminary phosphate simulation data analysis which indicated that a second-order reaction was more applicable. A report currently being prepared by CTSL [10] describes such nutrient and DO simulation studies. Source and sink terms in the DO budget have not been delineated to this extent in the Thomann Model nor can chlorophyll levels be simulated by linkage with the nitrogen cycle.

When initially applying the Dynamic Estuary Model to a given system, reasonable care is required in simulating the hydraulics to avoid major errors in the quality predictions. The values assumed for Manning roughness coefficients are particularly important since they influence both the tidal range and phasing. An optimum set of coefficients with verification based upon USC&GS tidal data should be determined by trial and error procedures prior to any quality simulations. Another factor warranting consideration in the hydraulic model is the time step used for the solution. In order to minimize hydrodynamic instability, a

stability criterion which relates channel length, wave celerity, and tidal velocity to the time step, must be satisfied. Once the stability criterion is met, selecting shorter time intervals would not improve the hydraulic predictions significantly.

A discussion of both models' sensitivity to the physical network detail was previously presented. The Thomann Model, possibly because of its averaging effect over long time periods, does not appear to be very sensitive to degree of segmentation. For the Potomac Estuary, segment lengths of 1 to 3 miles were adequate. The Dynamic Estuary Model appears to be considerably more sensitive to the refinement of the network based upon limited data pertaining to the two networks originally developed for the Thomann Model. However, it should be recognized that input requirements and computer time and output increase in proportion to the number of channels and junctions selected. Time and resource restraints must be weighed against accuracy of data required before an evaluation of the required network can be made.

Practically all of the prototype dye data were reasonably simulated with the Thomann and Dynamic Estuary Models. With sufficient manipulation of dispersion coefficients, it was possible to make reasonable simulations of the 1966 and 1969 Potomac Estuary chloride distributions using the Thomann Model and of a 5-month transient chloride condition (1965) using the DEM. From an engineering viewpoint, it is preferable to refine the hydrodynamics of a system by utilizing a real-time solution (such as the Dynamic Estuary Model) rather than to represent a gross tidal mixing

phenomenon with an empirically derived dispersion coefficient applicable only over a narrow range of prototype conditions. This is particularly significant when attempting to predict water quality behavior for future conditions significantly different from any experienced historically and for which the validity of the dispersion coefficients is uncertain. From a practical standpoint, however, the Thomann Model does offer expediency with minimum effort.

# APPENDIX

## A. POTOMAC DYE STUDY - 1969

### 1. Release Conditions

A 6-percent solution of Rhodamine WT dye was discharged continuously into the upper Potomac Estuary from November 2-14, 1969, via the District of Columbia's Blue Plains Sewage Treatment Plant outfall. This outfall extends to the main shipping channel approximately 900 feet from the eastern shore at a point 10.4 miles downstream from Chain Bridge. The dye solution was discharged into the elutriation washwater discharge sump which drains directly to the outfall. Initially, dye was pumped at a rate of 120 ml/min but a pump failure occurred during the second day of the study. It was therefore decided to use a siphoning procedure for the remaining 12 days.

Due to the imprecision of siphoning, it was necessary to recalibrate the discharge rate of 120 ml/min several times each day. As an additional check, the rectangular tank in which the dye solution was mixed was accurately measured to determine changes in the volume of dye. Volume changes for each 4-hour period of the study were recorded and subsequently converted to a mass basis. Table 1 presents volumes, discharge rates and related factors for the 13-day release period. Except for November 3 when a pump failure occurred and November 11-12 when a line became clogged, the dye injection rates (as shown in Table 1) were relatively uniform. During this release period, a total of 269 pounds of pure dye (4,454 pounds of 6-percent dye solution) was discharged to the Potomac Estuary.

Table 1
DYE INJECTION DATA
Blue Plains - November, 1969

| Date | Time Period | Average Dye Level (in) | Average Surface Area (sq-in) | Change in Dye Level (in) | Volume (cu-in) | Discharge Rate (ml/min) | Mass of Dye Solution (o%) Discharged (lbs) | Mass of Pure Dye Discharged (lbs) |
|---|---|---|---|---|---|---|---|---|
| 11-02 | 0800 - 1200 | 13.16 | 2532 | 0.57 | 1443 | 98.6 | 54.8 | 3.31 |
| | 1200 - 1600 | 12.58 | 2527 | 0.57 | 1440 | 98.4 | 54.7 | 3.30 |
| | 1600 - 2000 | 12.00 | 2522 | 0.57 | 1438 | 98.2 | 54.6 | 3.30 |
| | 2000 - 2400 | 11.44 | 2518 | 0.57 | 1435 | 98.0 | 54.5 | 3.29 |
| 11-03 | 0000 - 0400 | 11.08 | 2515 | 0.16 | 402 | 27.5 | 15.3 | 0.92 |
| | 0400 - 0800 | 11.00 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0800 - 1200 | 10.00 | 2506 | 2.00 | 5012 | 342.3 | 190.5 | 11.51 |
| | 1200 - 1600 | 8.75 | 2495 | 0.50 | 1248 | 85.2 | 47.4 | 2.86 |
| | 1600 - 2000 | 7.94 | 2488 | 1.12 | 2787 | 190.4 | 105.9 | 6.40 |
| | 2000 - 2400 | 7.12 | 2482 | 0.50 | 1241 | 84.8 | 47.2 | 2.85 |
| 11-04 | 0000 - 0400 | 6.56 | 2477 | 0.62 | 1536 | 104.9 | 58.4 | 3.53 |
| | 0400 - 0800 | 6.00 | 2472 | 0.50 | 1236 | 84.4 | 47.0 | 2.84 |
| | 0800 - 1200 | 5.40 | 2467 | 0.69 | 1702 | 116.2 | 64.7 | 3.91 |
| | 1200 - 1600 | 4.72 | 2461 | 0.69 | 1698 | 116.0 | 64.5 | 3.90 |
| | 1600 - 2000 | 17.40 | 2568 | 1.19 | 3056 | 208.7 | 116.1 | 7.01 |
| | 2000 - 2400 | 16.65 | 2561 | 0.31 | 794 | 54.2 | 30.2 | 1.82 |
| 11-05 | 0000 - 0400 | 16.22 | 2558 | 0.56 | 1432 | 97.8 | 54.4 | 3.29 |
| | 0400 - 0800 | 15.69 | 2553 | 0.50 | 1276 | 87.2 | 48.5 | 2.93 |
| | 0800 - 1200 | 15.22 | 2550 | 0.44 | 1122 | 76.6 | 42.6 | 2.57 |
| | 1200 - 1600 | 14.69 | 2545 | 0.62 | 1578 | 107.8 | 60.0 | 3.62 |
| | 1600 - 2000 | 13.94 | 2539 | 0.875 | 2222 | 151.8 | 84.4 | 4.01 |
| | 2000 - 2400 | 13.16 | 2532 | 0.69 | 1747 | 119.3 | 66.4 | 4.01 |
| 11-06 | 0000 - 0400 | 12.47 | 2526 | 0.685 | 1730 | 118.2 | 65.7 | 3.97 |
| | 0400 - 0800 | 11.81 | 2521 | 0.625 | 1576 | 107.6 | 59.9 | 3.62 |
| | 0800 - 1200 | 11.12 | 2515 | 0.75 | 1886 | 128.8 | 71.7 | 4.33 |
| | 1200 - 1600 | 10.42 | 2509 | 0.66 | 1656 | 113.1 | 62.9 | 3.80 |
| | 1600 - 2000 | 9.80 | 2504 | 0.59 | 1477 | 100.9 | 56.1 | 3.39 |
| | 2000 - 2400 | 8.78 | 2495 | 1.44 | 3593 | 245.4 | 136.5 | 8.24 |
| 11-07 | 0000 - 0400 | 7.62 | 2486 | 0.87 | 2163 | 147.7 | 82.2 | 4.97 |
| | 0400 - 0800 | 6.97 | 2480 | 0.44 | 1091 | 74.5 | 41.5 | 2.51 |
| | 0800 - 1200 | 6.25 | 2474 | 1.00 | 2474 | 169.0 | 94.0 | 5.68 |
| | 1200 - 1600 | 5.62 | 2469 | 0.25 | 617 | 42.1 | 23.5 | 1.42 |
| | 1600 - 2000 | 18.59 | 2578 | 0.44 | 1134 | 77.4 | 43.1 | 2.60 |
| | 2000 - 2400 | 18.06 | 2573 | 0.625 | 1608 | 109.8 | 61.1 | 3.69 |
| 11-08 | 0000 - 0400 | 17.47 | 2568 | 0.56 | 1438 | 98.2 | 54.6 | 3.30 |
| | 0400 - 0800 | 16.97 | 2564 | 0.44 | 1128 | 77.0 | 42.9 | 2.59 |
| | 0800 - 1200 | 16.50 | 2560 | 0.80 | 1280 | 87.4 | 48.6 | 2.94 |
| | 1200 - 1600 | 16.06 | 2556 | 0.38 | 971 | 66.3 | 36.9 | 2.23 |
| | 1600 - 2000 | 15.44 | 2551 | 0.875 | 2232 | 152.4 | 84.8 | 5.12 |
| | 2000 - 2400 | 14.69 | 2545 | 0.625 | 1591 | 108.7 | 60.5 | 3.65 |

DYE INJECTION DATA (Cont.)
Blue Plains - November, 1969

| Date | Time Period | Average Dye Level (in) | Average Surface Area (sq-in) | Change in Dye Level (in) | Volume (cu-in) | Discharge Rate (ml/min) | Mass of Dye Solution (6%) Discharges (lbs) | Mass of Pure Dye Discharged (lbs) |
|---|---|---|---|---|---|---|---|---|
| 11-09 | 0000 - 0400 | 14.03 | 2540 | 0.69 | 1753 | 119.7 | 66.6 | 4.02 |
| | 0400 - 0800 | 13.34 | 2534 | 0.69 | 1748 | 119.4 | 66.4 | 4.01 |
| | 0800 - 1200 | 12.56 | 2527 | 0.875 | 2211 | 151.0 | 84.0 | 5.07 |
| | 1200 - 1600 | 11.94 | 2522 | 0.38 | 958 | 65.4 | 36.4 | 2.20 |
| | 1600 - 2000 | 11.28 | 2516 | 0.94 | 2365 | 161.5 | 89.9 | 5.43 |
| | 2000 - 2400 | 10.47 | 2510 | 0.69 | 1732 | 118.3 | 65.8 | 3.98 |
| 11-10 | 0000 - 0400 | 9.78 | 2504 | 0.69 | 1728 | 118.0 | 65.7 | 3.97 |
| | 0400 - 0800 | 9.10 | 2498 | 0.69 | 1724 | 117.8 | 65.5 | 3.96 |
| | 0800 - 1200 | 8.47 | 2493 | 0.56 | 1396 | 95.4 | 53.1 | 3.21 |
| | 1200 - 1600 | 8.03 | 2489 | 0.31 | | | | |
| | | 13.69 | 2537 | 0.375 | 1723 | 117.7 | 65.5 | 3.96 |
| | 1600 - 2000 | 13.12 | 2532 | 0.75 | 1899 | 129.7 | 72.2 | 4.36 |
| | 2000 - 2400 | 12.38 | 2526 | 0.75 | 1895 | 129.4 | 72.0 | 4.35 |
| 11-11 | 0000 - 0400 | 11.62 | 2519 | 0.75 | 1889 | 129.0 | 71.8 | 4.34 |
| | 0400 - 0800 | 10.69 | 2512 | 1.125 | 2826 | 193.0 | 107.4 | 6.49 |
| | 0800 - 1200 | 9.94 | 2505 | 0.375 | 939 | 64.1 | 35.7 | 2.16 |
| | 1200 - 1600 | 9.69 | 2503 | 0.125 | 313 | 21.4 | 11.9 | 0.72 |
| | 1600 - 2000 | 9.56 | 2502 | 0.125 | 313 | 21.4 | 11.9 | 0.72 |
| | 2000 - 2400 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| 11-12 | 0000 - 0400 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0400 - 0800 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0800 - 1200 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 1200 - 1600 | 9.25 | 2500 | 0.50 | 1250 | 85.4 | 47.5 | 2.87 |
| | 1600 - 2000 | 8.50 | 2493 | 1.00 | 2493 | 170.3 | 94.7 | 5.72 |
| | 2000 - 2400 | 7.88 | 2488 | 0.25 | 622 | 42.5 | 23.6 | 1.43 |
| 11-13 | 0000 - 0400 | 7.69 | 2486 | 0.125 | 311 | 21.2 | 11.8 | 0.72 |
| | 0400 - 0800 | 7.44 | 2484 | 0.375 | 932 | 63.7 | 35.4 | 2.14 |
| | 0800 - 1200 | 7.12 | 2482 | 0.25 | 620 | 42.4 | 23.6 | 1.43 |
| | 1200 - 1600 | 6.42 | 2476 | 1.17 | 2897 | 197.9 | 110.0 | 6.64 |
| | 1600 - 2000 | 5.23 | 2466 | 1.20 | 2959 | 202.1 | 112.4 | 6.79 |
| | 2000 - 2400 | 4.06 | 2456 | 1.13 | 2775 | 189.5 | 105.5 | 6.37 |
| 11-14 | 0000 - 0400 | 3.00 | 2447 | 1.00 | 2447 | 167.1 | 93.0 | 5.62 |
| | 0400 - 0800 | 2.00 | 2438 | 1.00 | 2438 | 166.5 | 92.6 | 5.59 |
| | 0800 - 1200 | 1.00 | 2430 | 1.00 | 2430 | 166.0 | 92.4 | 5.58 |
| | 1200 - 1600 | 0.25 | 2424 | 0.875 | 2121 | 144.9 | 80.6 | 4.87 |
| | | | TOTALS | | 117,200 | | 4,454 | 269 |

2. Monitoring System

a. Longitudinal Stations (Slack Tide)

Longitudinal sampling in the Potomac Estuary from Key Bridge to Sandy Point during high- and low-slack tide periods was conducted by CTSL. Data from 10 low-slack sampling runs and eight high-slack runs were obtained during the period November 3-December 1. A tabulation of the data as analyzed by the U. S. Geological Survey is included in this appendix.

Surface samples at mid-channel were collected from 18 stations for longitudinal monitoring of the dye release. A listing of these stations is given in Table 2.

b. Lateral and Vertical Stations

To determine the lateral and vertical mixing of the dye, transect sampling was conducted by CTSL at 14 stations, all of which coincided with the longitudinal sampling stations. These transect stations are shown in Table 2.

Five transect sampling runs were made during the period November 4-20. Due to the considerable amount of time required for transect sampling, it was not possible to limit sampling to slack-tide periods. Cross-sectional area profiles showing the sampling grids used for each station are presented in the appendix. As can be seen from these profiles, eight to 17 samples were collected at each station. It should be noted that many of the transects extended into the major embayments.

Table 2

LONGITUDINAL SAMPLING STATIONS
Potomac River

| Station Number | Location | Miles Below Chain Bridge |
|---|---|---|
| 1 * | Key Bridge | 3.35 |
| 1A | Memorial Bridge | 4.85 |
| 2 * | 14th Street Bridge | 5.90 |
| 2A | Buoy N "6" | 6.70 |
| 3 * | Hains Point | 7.60 |
| 3A | Hunter's Point | 8.70 |
| 4 * | Bellevue | 10.00 |
| 4A* | Goose Island | 11.05 |
| 5 * | Woodrow Wilson Bridge | 12.10 |
| 5A | Rosier Bluff | 13.55 |
| 6 * | Broad Creek | 15.20 |
| 7 * | Piscataway Creek | 18.35 |
| 8 * | Dogue Creek | 22.30 |
| 8A* | Gunston Cove | 24.30 |
| 9 * | Hallowing Point | 26.90 |
| 10 * | Indian Head | 30.60 |
| 11 | Possum Point | 38.00 |
| 12 | Sandy Point | 42.50 |

* Also transect stations

3. Presentation of Data

a. Tidal Conditions and Hydrology

The tidal conditions in the upper Potomac Estuary at Washington, D. C. are monitored routinely by the U. S. Coast and Geodetic Survey. Figures 1, 2, and 3 present actual tidal data at Washington for most of November 1969 and the mean tidal height at this station for the entire period of record.

As can be seen in Figures 1 through 3, there were three distinct tidal conditions during November. The first 3 days of the month were characterized by atypically high tides with considerable fluctuations in the tidal range. The predominately northwesterly winds which occurred on November 3-6 were responsible for the steadily decreasing tidal levels shown during this period. These extremely low tides had a pronounced effect on the downstream movement of dye. The remaining 3 weeks showed generally normal tidal ranges with average heights approximating the mean-tide condition. The slight decrease in tidal levels on November 19-21 was again attributed to high northwesterly winds.

Average daily flows measured at Great Falls during November 1969 are shown in Figure 4. Freshwater inflows to the upper Potomac Estuary, like tides, were influenced greatly by climatological conditions. As indicated in Figure 4, two separate flow regimes occurred. The period November 1-5 had an average flow of 1,886 cfs whereas during the remainder of the month, the average flow was 3,974 cfs. Daily flows within each period were uniform, however.

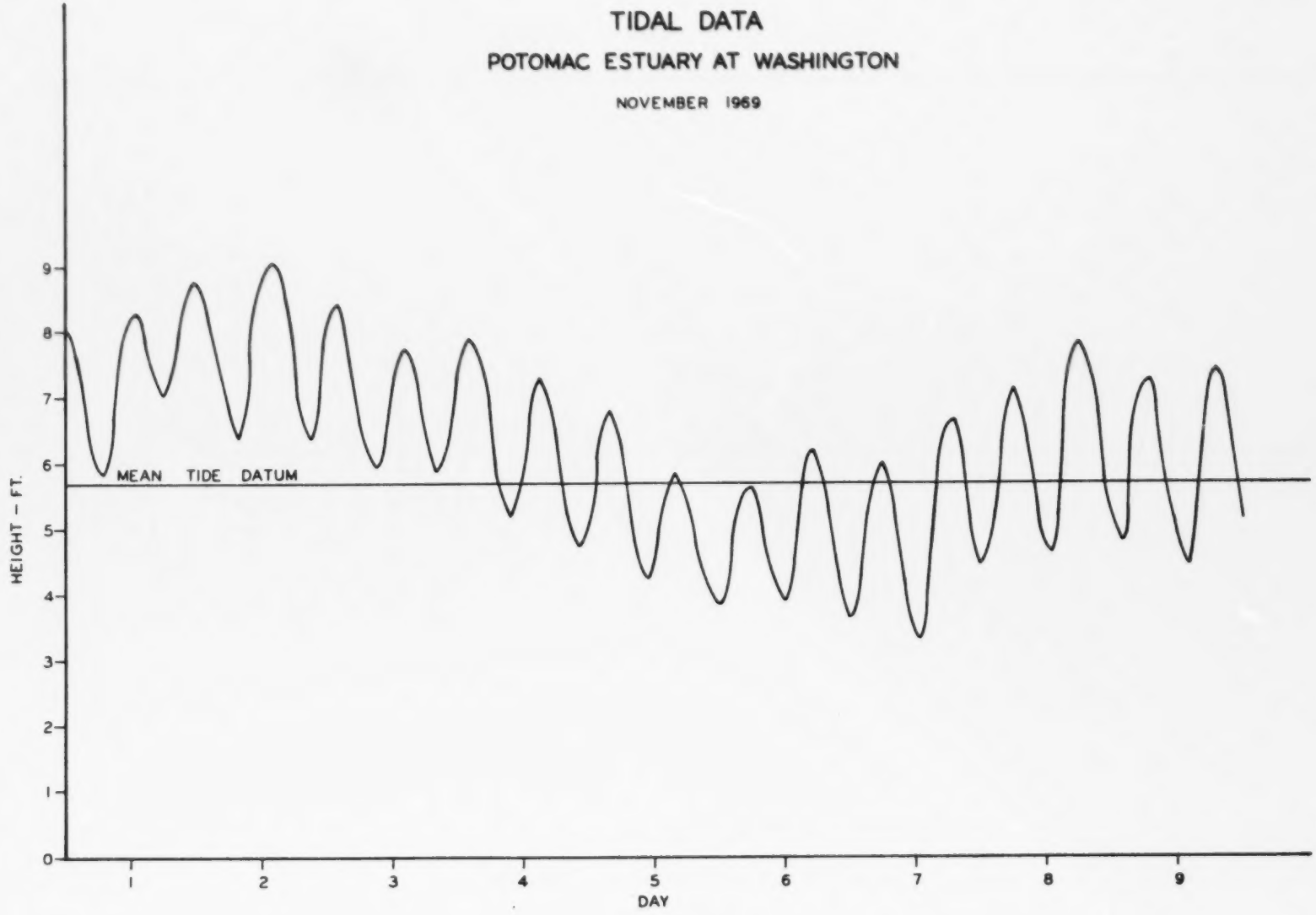

TIDAL DATA
POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969
HEIGHT - FT.
MEAN TIDE DATUM
0
1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7
8
9
DAY

FIGURE - A 1

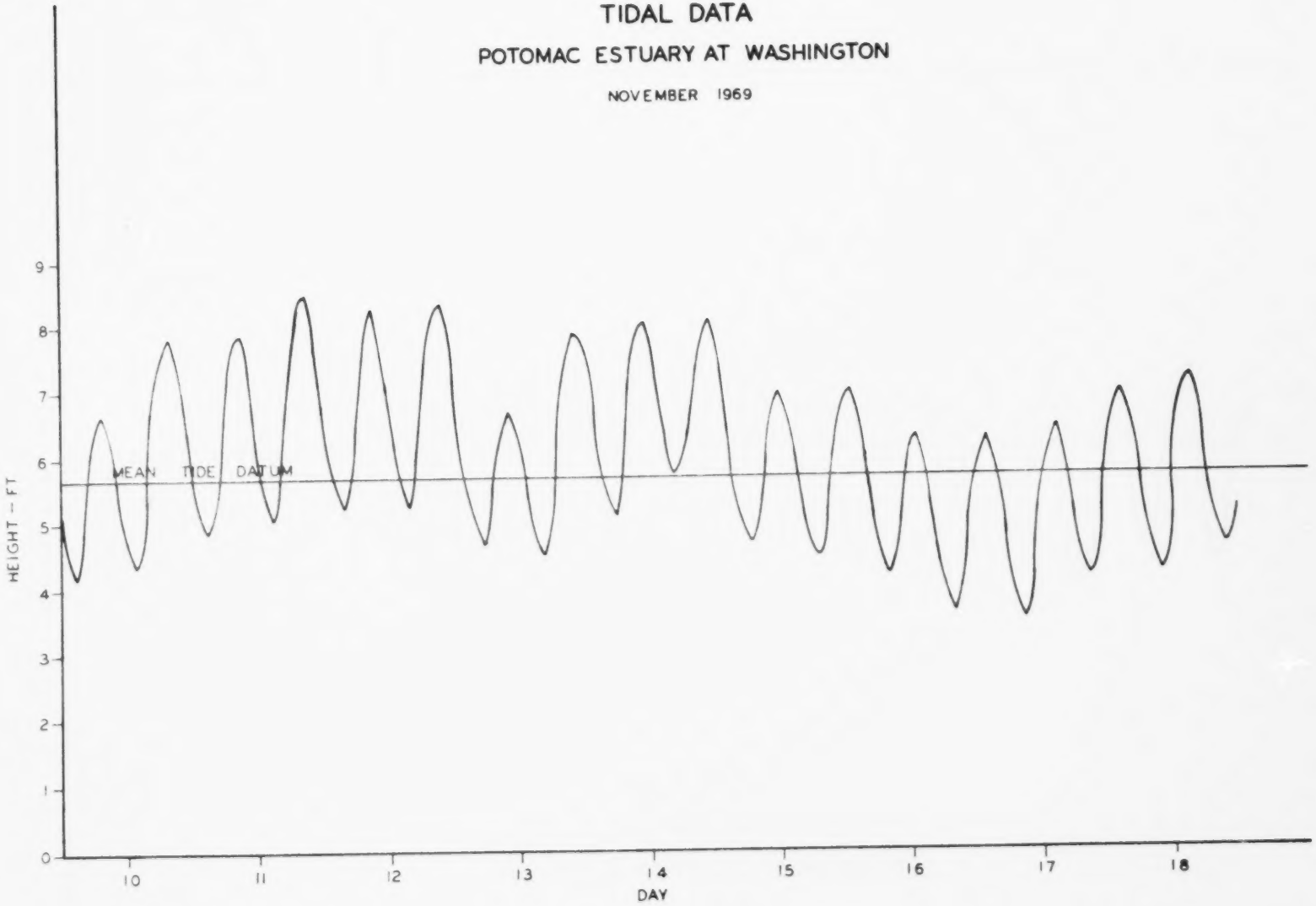

TIDAL DATA
POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969
HEIGHT - FT
MEAN TIDE DATUM
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
DAY

FIGURE - A 2

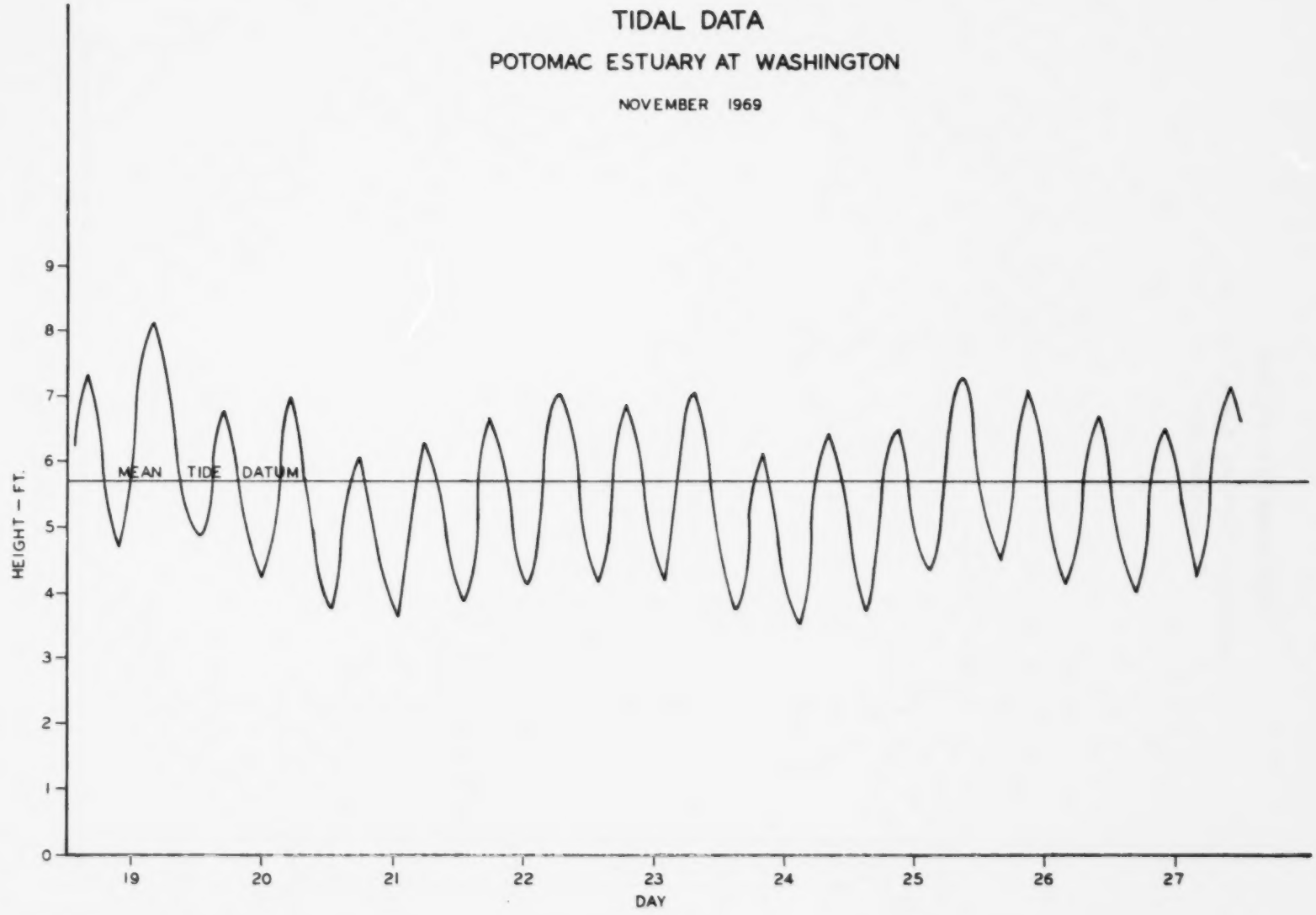

TIDAL DATA
POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969
HEIGHT - FT.
MEAN TIDE DATUM
0
1
2
3
4
5
6
7
8
9
19
20
21
22
23
24
25
26
27
DAY

FIGURE - A 3

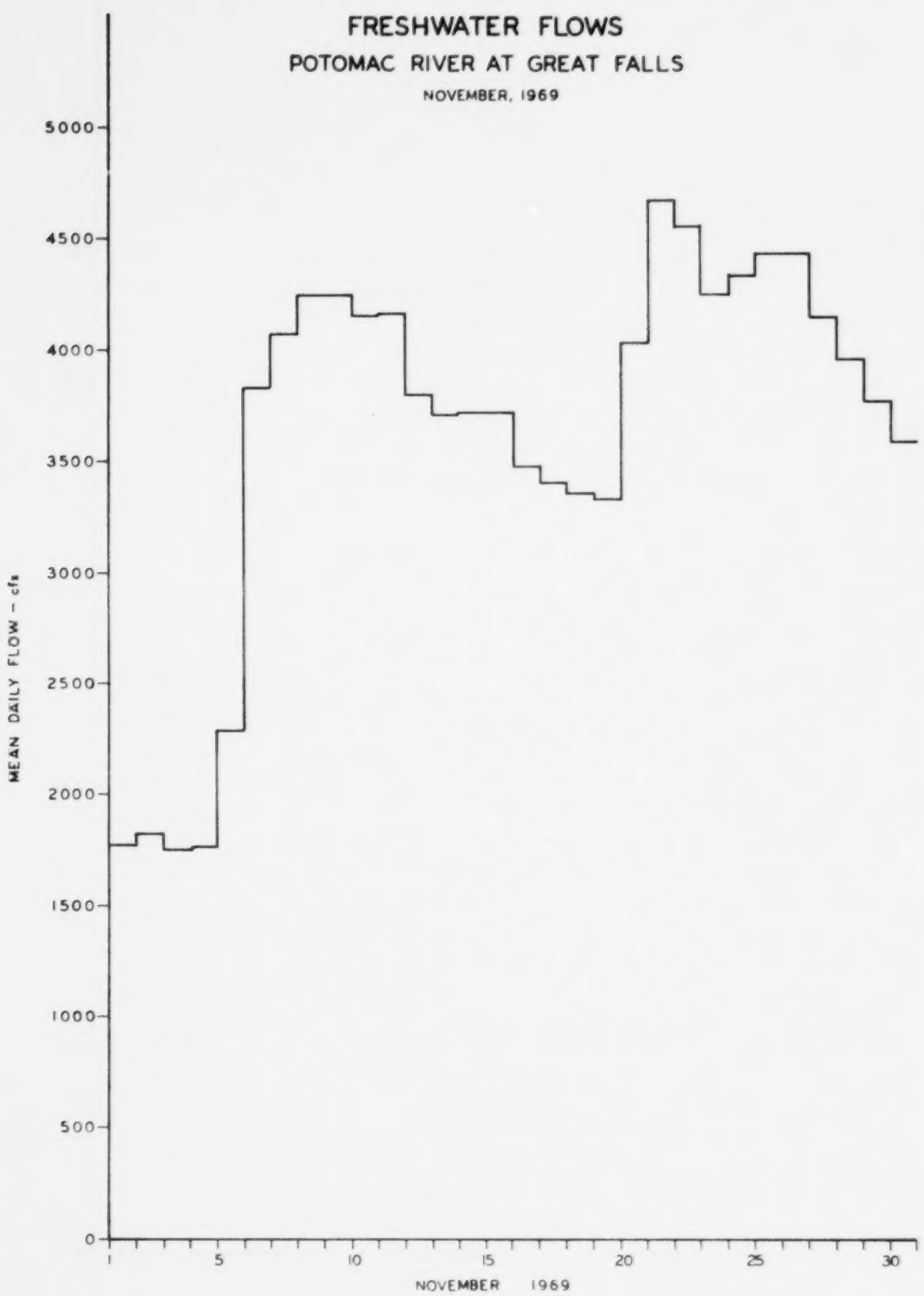

FRESHWATER FLOWS
POTOMAC RIVER AT GREAT FALLS
NOVEMBER, 1969
MEAN DAILY FLOW - cfs
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
5
10
15
20
25
30
NOVEMBER 1969

FIGURE - A 4

Freshwater inflows account for the net advective downstream movement in a tidal system. They can also greatly affect its dispersion characteristics. Because of their importance, freshwater flows must be defined and incorporated into the hydrodynamics of a tidal system if mathematical model simulation studies are to be successful.

b. Dye Movement

The upper Potomac Estuary dye data obtained from longitudinal sampling stations between Key Bridge and Possum Point are presented in isopleth form in Figure 5 (low-slack data) and Figure 6 (high-slack data). Although dye was discharged at River Mile 10.4, Figure 5 indicates that maximum dye buildup occurred between River Mile 14 and 15. Dye concentrations between 1.0 and 2.0 ppb were observed in this area on November 5, three days after dye was initially discharged. The fact that dye peaks were located 5 miles downstream from the discharge point may have been due to (1) dye injected at a 14-foot depth with samples collected at the surface, (2) freshwater inflows which caused net downstream advective movement, (3) sampling performed at low-slack tide when maximum downstream movement could be expected. The effects of item (3) are evident when Figures 5 and 6 are compared. The high-slack tide data shown in Figure 6 indicate that maximum dye concentrations (> 1.0 ppb) occurred between River Mile 8 and 11, or approximately a complete tidal excursion range upstream from the low-slack tide peaks.

Longitudinal dye movement can be readily identified in the two isopleths. The dye cloud spread rapidly between Hains Point and Piscataway Creek as shown in Figure 5. In 3 days, it moved approximately 5 miles upstream beyond the 14th Street Bridge and approximately 14 miles downstream to Gunston Cove. This represented movement rates of 1.7 mi/day and 4.7 mi/day, respectively. The especially high downstream movement can be attributed to the very low tides observed during this

period (see previous section). Downstream movement rates beyond November 5 can be estimated from the slopes of the concentration lines shown in Figures 5 and 6. The rates generally range from approximately 0.8 mi/day to 1.2 mi/day with an average of 1.1 mi/day. These rates apply only to a freshwater inflow of 4,000 cfs.

Dye was initially detected at Indian Head on November 15 and at Possum Point on November 19. Both time periods yield an average downstream movement rate of approximately 1.6 mi/day. An instantaneous dye release study conducted in the upper Potomac Estuary by the U. S. Geological Survey in August 1965 [2] showed the average velocity of net downstream movement of the dye mass centroid to be 0.6 mi/day. It should be noted, however, that the tides were relatively stable during the USGS study and that freshwater flows at Great Falls varied between 700 and 1,200 cfs, considerably smaller flows than those encountered during the 1969 dye study. The rates of movement of the leading edge and the centroid of the dye mass may also differ appreciably.

Data collected from the three complete transect runs--November 11, 18, and 20--between the 14th Street Bridge and Indian Head are plotted in Figures 7, 8, and 9. The ranges in dye concentration at each transect station and in the major embayments, mean concentrations at each transect (excluding embayments), and mid-channel concentrations are shown in these figures. Mid-channel stations correspond with the longitudinal sampling

stations discussed previously. The stations comprising a transect were selected in such a way that each would have about equal weight in terms of the cross-sectional area and the flow represented.

In most cases, the total dye concentration range for a given transect was within 0.3 ppb which indicated that considerable lateral and vertical mixing had actually occurred. According to Figures 7 and 9, the dye concentration ranges measured in Broad Creek, Piscataway Creek, Dogue Creek, and Gunston Cove were generally representative of data collected at comparable main-channel stations. The extent of dye intrusion into these embayments was substantial, further indicating that tidal exchanges between the main channel and adjoining embayments should definitely be considered and, if possible, incorporated in mathematical modeling studies.

To assist in the interpretation of simulated and observed data for model verification purposes, an analysis was made of the average concentration for transect and mid-channel (surface) values. Figures 7, 8, and 9 generally show relatively small differences ($< 0.5$ ppb) between these two sets of data. Therefore, it would appear to be valid to compare the model predictions for a given segment with the results obtained from longitudinal sampling within that segment. Where larger deviations between mean and mid-channel concentrations were noted, no significant conclusions could be drawn concerning their relative magnitudes.

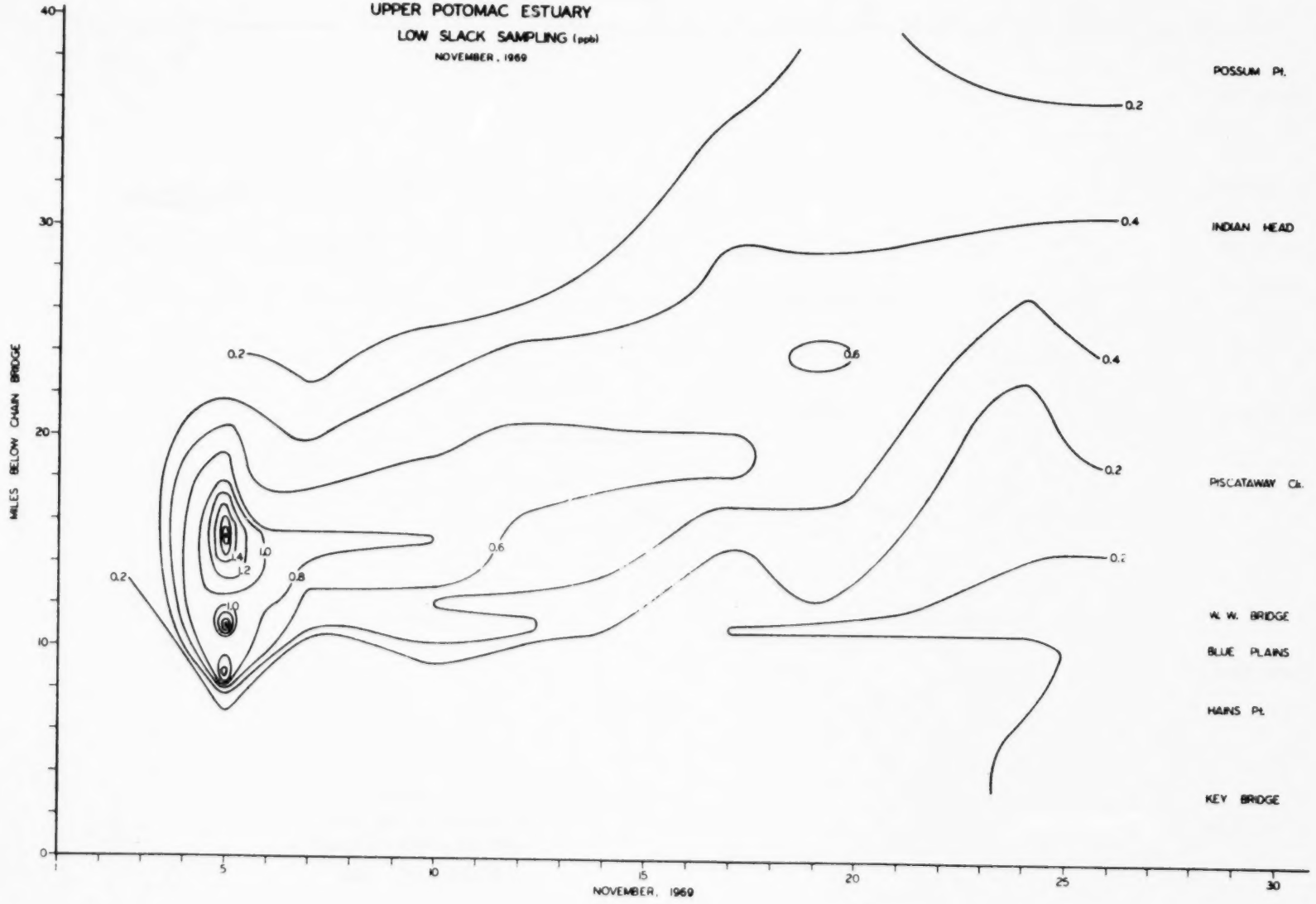

DYE ISOPLETH
UPPER POTOMAC ESTUARY
LOW SLACK SAMPLING (ppb)
NOVEMBER, 1969
MILES BELOW CHAIN BRIDGE
NOVEMBER, 1969
POSSUM PT.
INDIAN HEAD
PISCATAWAY Ck.
W. W. BRIDGE
BLUE PLAINS
HAINS PT.
KEY BRIDGE
0.2
0.4
0.6
0.8
1.0
1.2
1.4

FIGURE - A 5

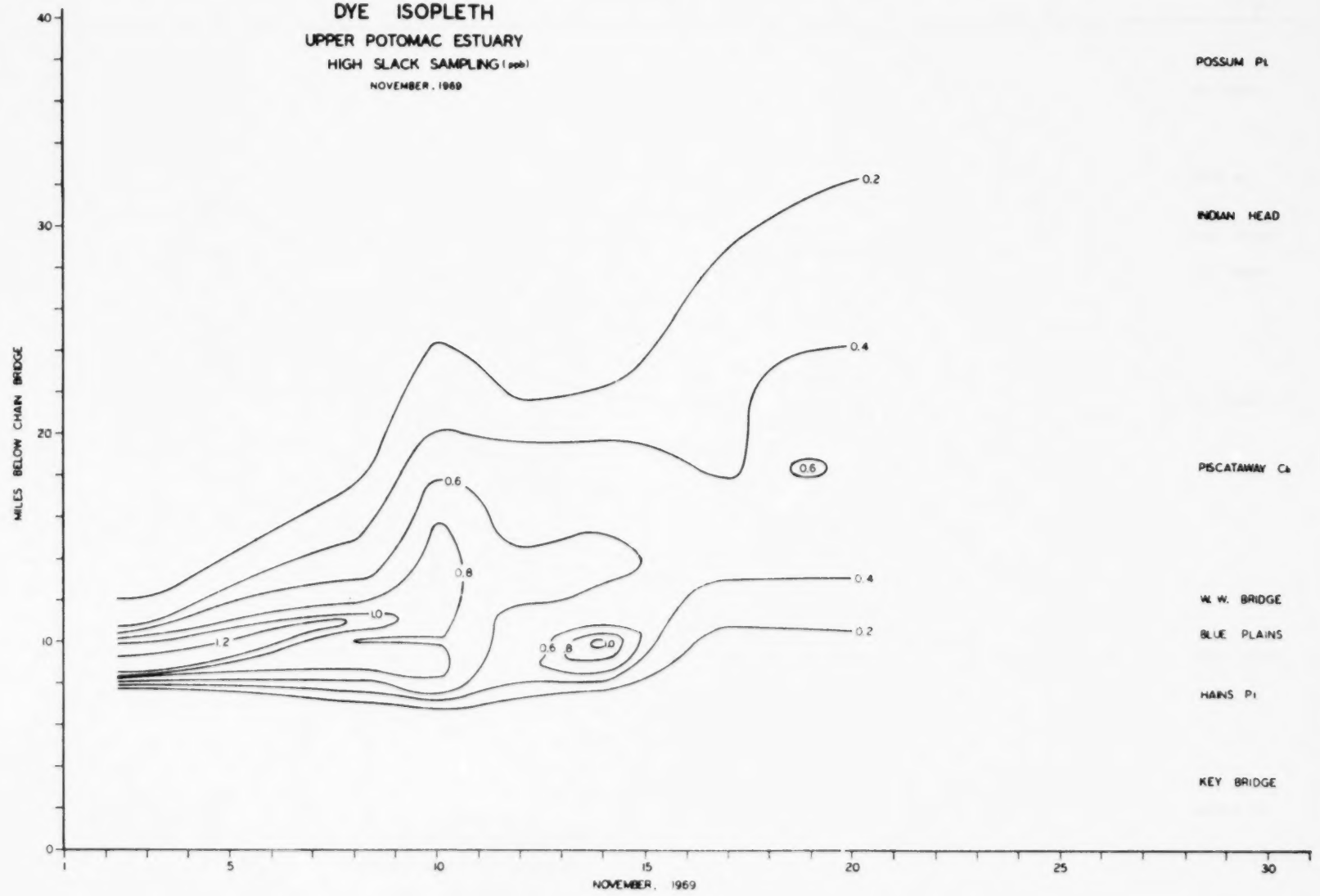

DYE ISOPLETH
UPPER POTOMAC ESTUARY
HIGH SLACK SAMPLING (ppb)
NOVEMBER, 1969
MILES BELOW CHAIN BRIDGE
40
30
20
10
0
0.2
0.4
0.6
0.8
1.0
1.2
0.6
0.8
1.0
0.4
0.2
1
5
10
15
20
25
30
NOVEMBER, 1969
POSSUM PT.
INDIAN HEAD
PISCATAWAY CR.
W. W. BRIDGE
BLUE PLAINS
HAINS PT.
KEY BRIDGE

FIGURE - A 6

# TRANSECT DYE SAMPLING SUMMARY

## UPPER POTOMAC ESTUARY

NOVEMBER 11, 1969

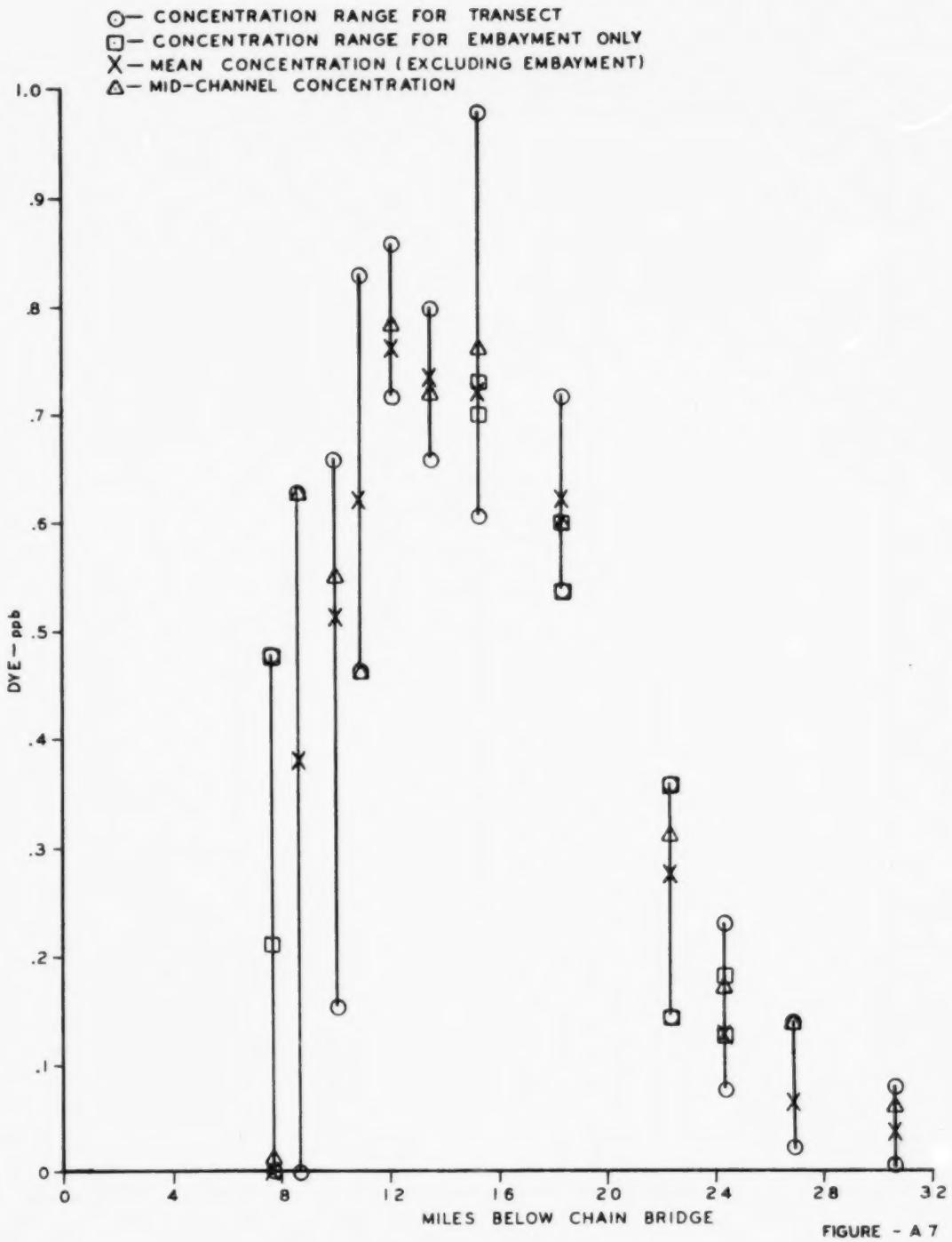



FIGURE - A 7

# TRANSECT DYE SAMPLING SUMMARY

## UPPER POTOMAC ESTUARY

NOVEMBER 18, 1969

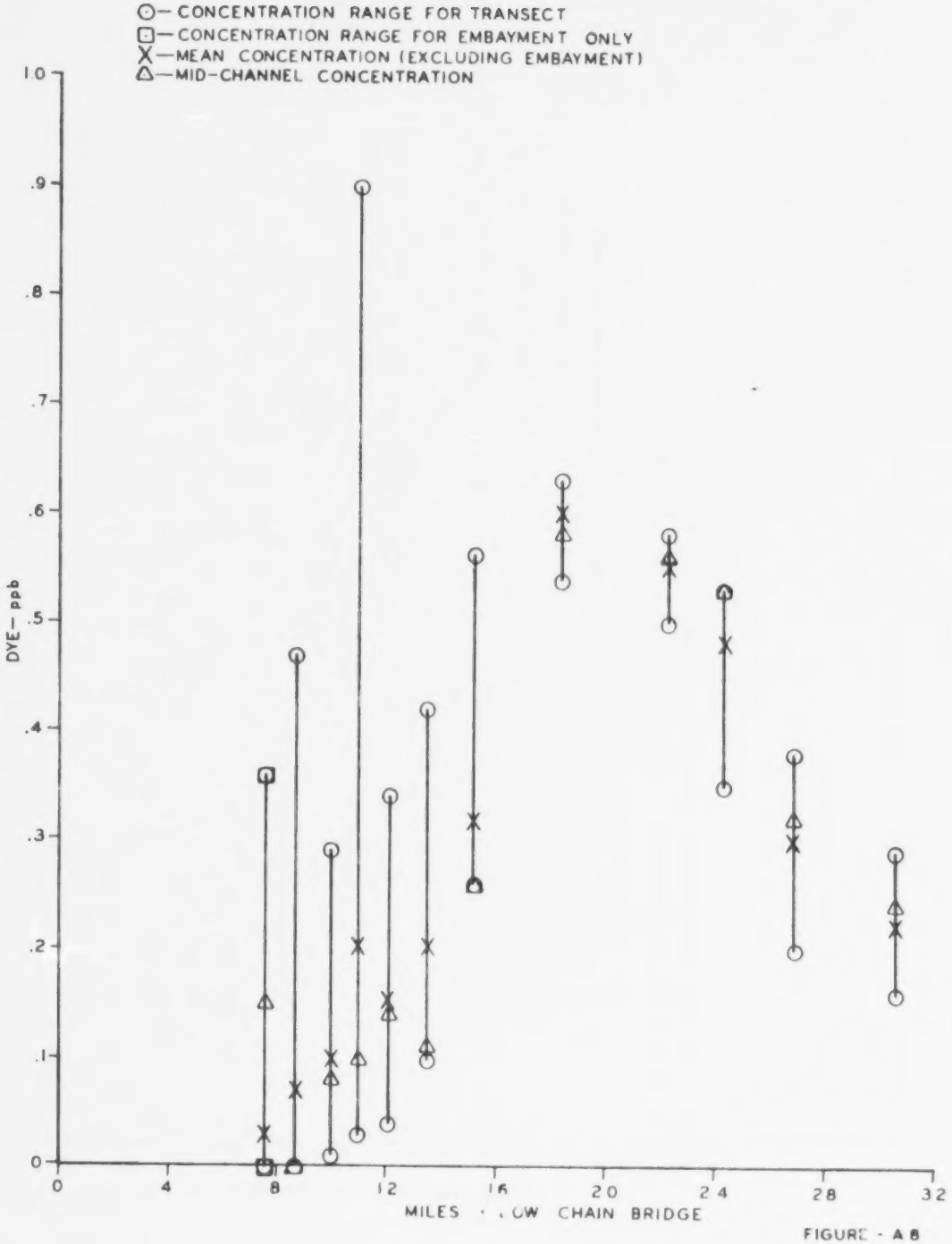



FIGURE - A 8

# TRANSECT DYE SAMPLING SUMMARY

## UPPER POTOMAC ESTUARY

NOVEMBER 20, 1969

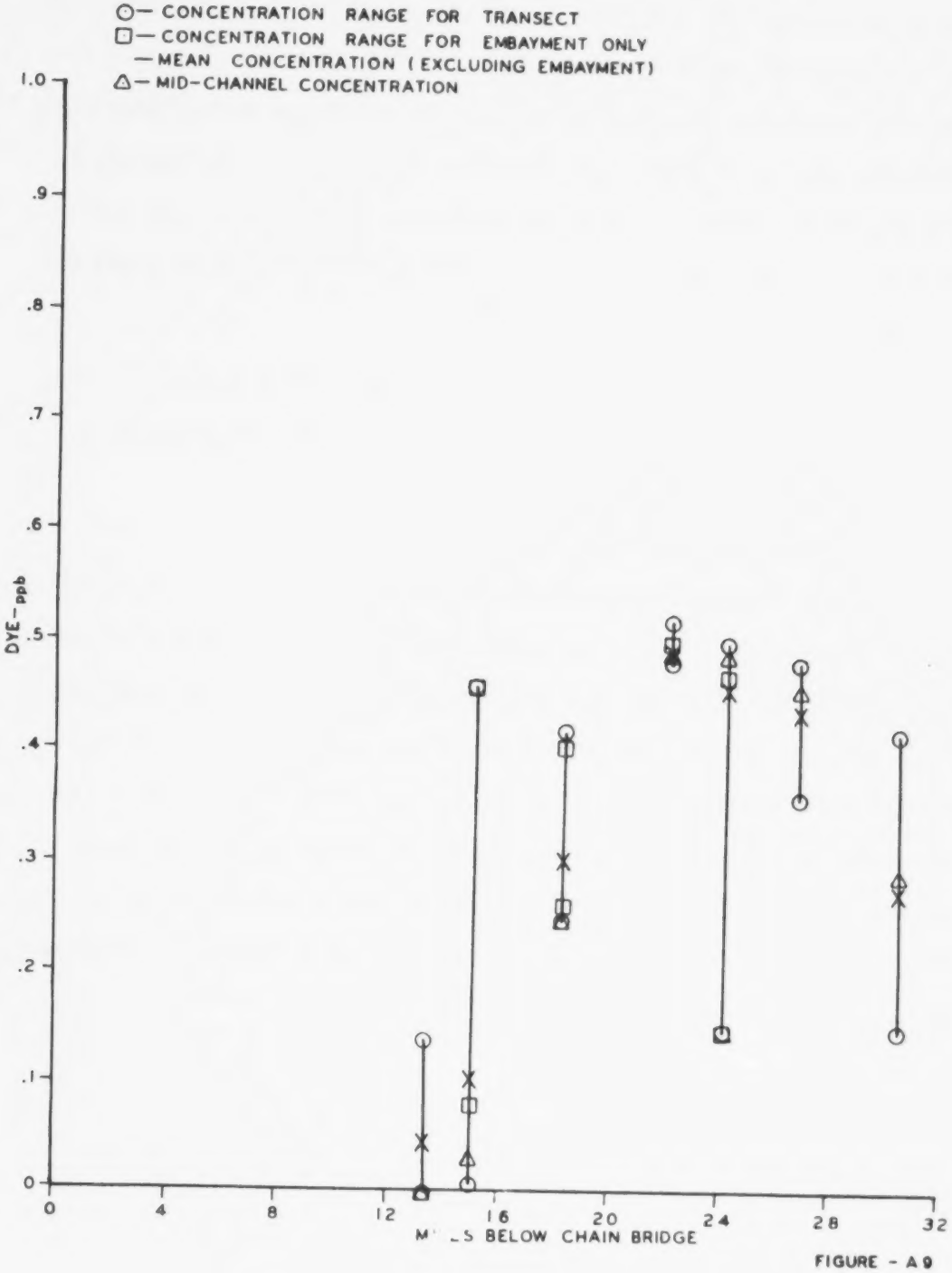



FIGURE - A9

c. Loss Rate Determination

The dye loss rate considers not only a decay or adsorption phenomenon but also reflects the inability to detect dye at low concentrations. It was estimated by computing the rate of change in the total dye mass as measured throughout the upper estuary during an 18-day period immediately following the dye release. Longitudinal sampling data, supplemented by two sets of transect data, were converted from concentrations to mass loadings per lineal foot of estuary according to the following equation:

$$\text{Mass (lbs/lineal ft.)} = \frac{C \times A \times 62.4}{10^9}$$

where: C = dye concentration (ppb) for a given sampling station

A = cross-sectional area ($ft^2$) at the sampling station

62.4 = mass of 1 cubic foot of water, and

$10^9$ = conversion factor

The mass loadings obtained were plotted as a function of distance and fitted with smooth curves. The areas under these curves were planimetered to determine the total dye mass observed at a given time. As shown in Figure 10, all such dye masses for the 18-day period appear to follow a first-order reaction. The slope of the resulting line, which is the dye loss rate, was calculated to be 0.030 per day (base e). A 1965 upper Potomac Estuary dye study by Hetling and O'Connell [3] yielded a dye loss rate of 0.034 per day (base e) which was calculated utilizing a similar approach.

The dye masses computed from measured data were always greater than the actual masses discharged during the release period. By the end of the release period (November 14), approximately 350 pounds of dye were computed to be in the estuary whereas only 269 pounds had been discharged. This 80-pound difference, excluding dye losses to November 14, can perhaps be attributed to (1) naturally occurring background fluoresence which was not defined quantitatively, (2) possible unrepresentative sampling, especially near the injection site, or (3) inaccuracy in analysis. For purposes of computing dye loss rate, these factors should have a uniform relationship over the entire sampling period.

# DYE LOSS RATE

## UPPER POTOMAC ESTUARY

NOVEMBER 1969

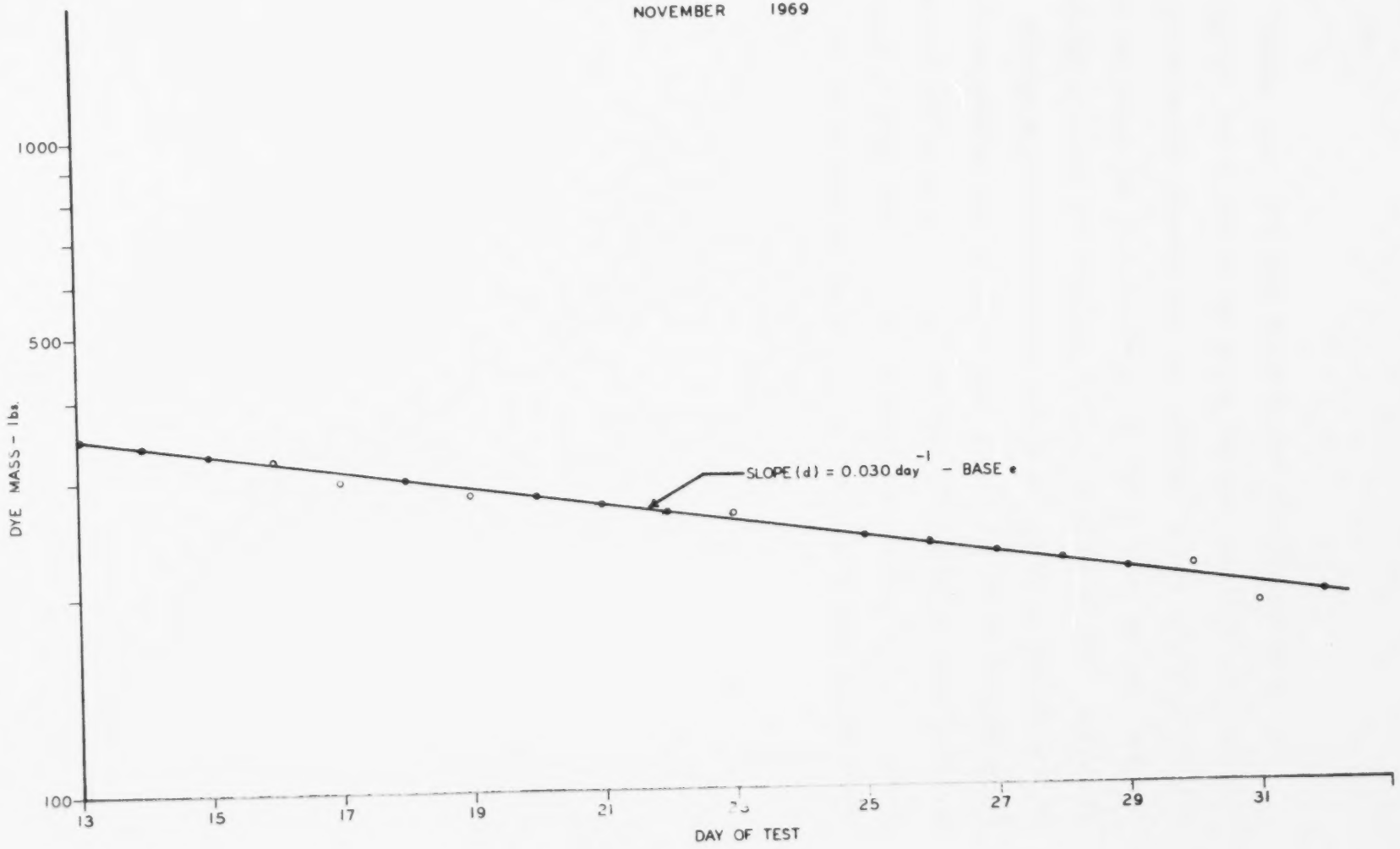



FIGURE - A 10

## B. ANACOSTIA DYE STUDY - 1970

### 1. Release Conditions

A 20-percent solution of Rhodamine WT dye was discharged continuously into the Anacostia River from April 22-28, 1970, to determine the advective transport characteristics of the Anacostia tidal system and to provide additional data upon which mathematical model verification studies could be based. The dye was discharged into the main channel of the Anacostia River approximately 1 foot below the low water surface at the Washington Suburban Sanitary Commission's marina in Bladensburg, Maryland (River Mile 8.1). This area exhibits an average tidal range of approximately 3 feet but nontidal conditions exist 1/2 mile upstream.

A diaphragm type controlled volume pump, precalibrated to discharge 40 lbs/day, was utilized for this study. The container of dye was placed on a scale so that weight could be read and recorded several times each day as a further check of the actual mass pumped. A total of 280 pounds of the 20-percent dye solution or 56 pounds of pure dye was discharged to the Anacostia during this study.

2. Monitoring System

Longitudinal monitoring of the dye cloud was performed daily during periods of high- and low-slack water. Coverage extended from the confluence of the Northeast and Northwest Branches to the mouth of the Anacostia River at Hains Point. Thirteen high-slack and 10 low-slack water sampling runs were made during the period April 22-May 27. All samples were analyzed by CTSL using a Turner fluorometer modified with a high sensitivity kit to obtain concentrations as low as 0.1 ppb. The sampling data is shown in this appendix.

There were 19 stations routinely sampled. All samples were collected at mid-channel and within 1 foot of the surface. A description of these stations is presented in Table 3.

In addition to the stations given in Table 3, several samples were collected within Kingman Lake to determine the effect of tidal exchange between this embayment and the main stem Anacostia River. However, neither lateral nor vertical sampling was routinely performed at any of the sampling stations. As was discussed in a previous chapter on model verification, the lack of transect data raised some doubt as to the representativeness of those stations actually sampled.

Table 3

LONGITUDINAL SAMPLING STATIONS
Anacostia River

| Station Number | Location | Miles Upstream from Mouth |
|---|---|---|
| 1 | Hains Point | 0.00 |
| 2 | Mouth of Washington Channel | - |
| 3 | Opposite U. S. Naval Station | 0.55 |
| 4 | Upstream from Buzzard Point | 1.00 |
| 5 | Douglass Bridge | 1.45 |
| 6 | Opposite Washington Naval Yard | 1.95 |
| 7 | 11th Street Bridge | 2.45 |
| 8 | Sousa Bridge | 3.10 |
| 9 | Southern Entrance to Kingman Lake | 3.75 |
| 10 | East Capitol Street Bridge | 4.35 |
| 11 | Benning Bridge | 4.90 |
| 12 | Northern Entrance to Kingman Lake | 5.65 |
| 13 | Opposite Kenilworth Aquatic Gardens | 6.25 |
| 14 | Route 50 Bridge | 6.90 |
| 16 | Upstream from Unnamed Tributary | 7.45 |
| 17 | Southern Edge of Marina | 7.95 |
| 18 | Bladensburg Road Bridge | 8.45 |
| 19 | Northwest Branch at Rhode Island Avenue Bridge | - |
| 20 | Northeast Branch at Baltimore Avenue Bridge | 9.00 |

3. Presentation of Data

a. Tidal Conditions and Hydrology

There are no tidal monitoring stations in the Anacostia River and consequently detailed tidal data during the dye study were not obtained. It has been reported by the U. S. Coast and Geodetic Survey that the mean tidal range at both Benning Bridge and Anacostia Bridge is 2.9 feet. The observed tidal range at the Bladensburg marina, which is farther upstream, was also estimated to be approximately 3 feet. Time differences for Benning Bridge referenced to the Washington gage average +16 minutes for high water and +04 minutes for low water.

Average daily flows entering the tidal portion of the Anacostia River were measured by USGS gaging stations on the Northwest Branch at Hyattsville and the Northeast Branch at Riverdale. The flows for the study period are shown in Figure 11. Except for the initial 9 days when flows averaged 180 cfs, the freshwater inflows were generally between 60 and 100 cfs. Unusually high flows, i.e., 200-500 cfs, also occurred during the study but they were "flashy" in nature.

b. Dye Movement

The Anacostia River dye data obtained from the sampling stations outlined previously are presented in isopleth form in Figure 12 (high-slack data) and Figure 13 (low-slack data). As can be seen in Figure 12, maximum dye concentrations were observed at River Mile 7.5 on April 27-28, which were the last two days of dye discharge. Concentrations in this area were initially 6 to 7 ppb but as the study progressed, dye concentrations exceeded 10 ppb. Figure 13 also showed a maximum dye buildup of similar magnitude on April 27-28 but at River Mile 6.9. Evidently, the 0.6 mile difference can be attributed to the tidal excursion between slack water periods. The relatively high freshwater flows that occurred prior to April 28 were probably responsible for the net advective downstream movement of the dye peak from River Mile 8.1 to River Mile 7.5 or 6.9, depending on the tidal phase.

The longitudinal dye movement occurred quite rapidly between the point of injection and the southern entrance to Kingman Lake. Under low-slack conditions, when maximum downstream movement could be expected, dye concentrations exceeding 1.0 ppb were observed at that downstream station the second day (April 23) after discharge started. This translates to a velocity of approximately 2.5 mi/day. The rate of dye movement decreased farther downstream due to a significant increase in the volume of the Anacostia River. From April 23 to May 4, the average rate of downstream movement based upon the slopes of the concentration lines shown in Figure 13 was approximately 0.3 mi/day for the existing flows.

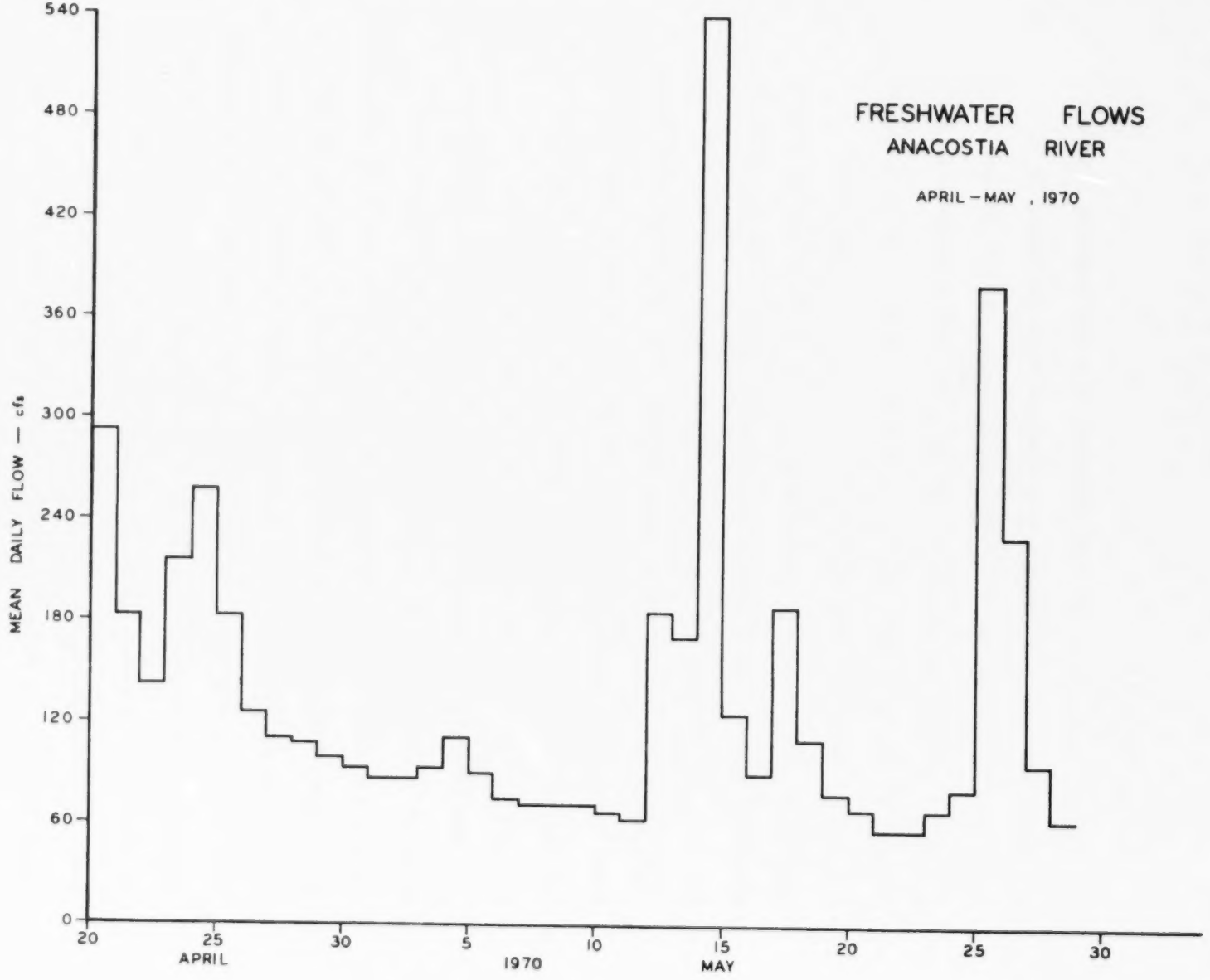

FRESHWATER FLOWS
ANACOSTIA RIVER
APRIL – MAY , 1970
MEAN DAILY FLOW — cfs
540
480
420
360
300
240
180
120
60
0
20
25
30
5
10
15
20
25
30
APRIL
1970
MAY

FIGURE - A 11

During this period, the leading edge of the dye cloud progressed downstream to the mouth of the Anacostia River.

As shown in Figures 12 and 13, there was very little upstream movement of the dye which is attributable to the fact that tidal effects do not extend much above the discharge point. Moreover, the trailing edge of the dye cloud appeared to move downstream at a slightly greater rate than the leading edge. The samples collected within Kingman Lake indicated that comparable amounts of dye were present there as in adjacent reaches of the main stem Anacostia River. The tidal and mass exchange between these two bodies of water therefore appears to be quite significant.

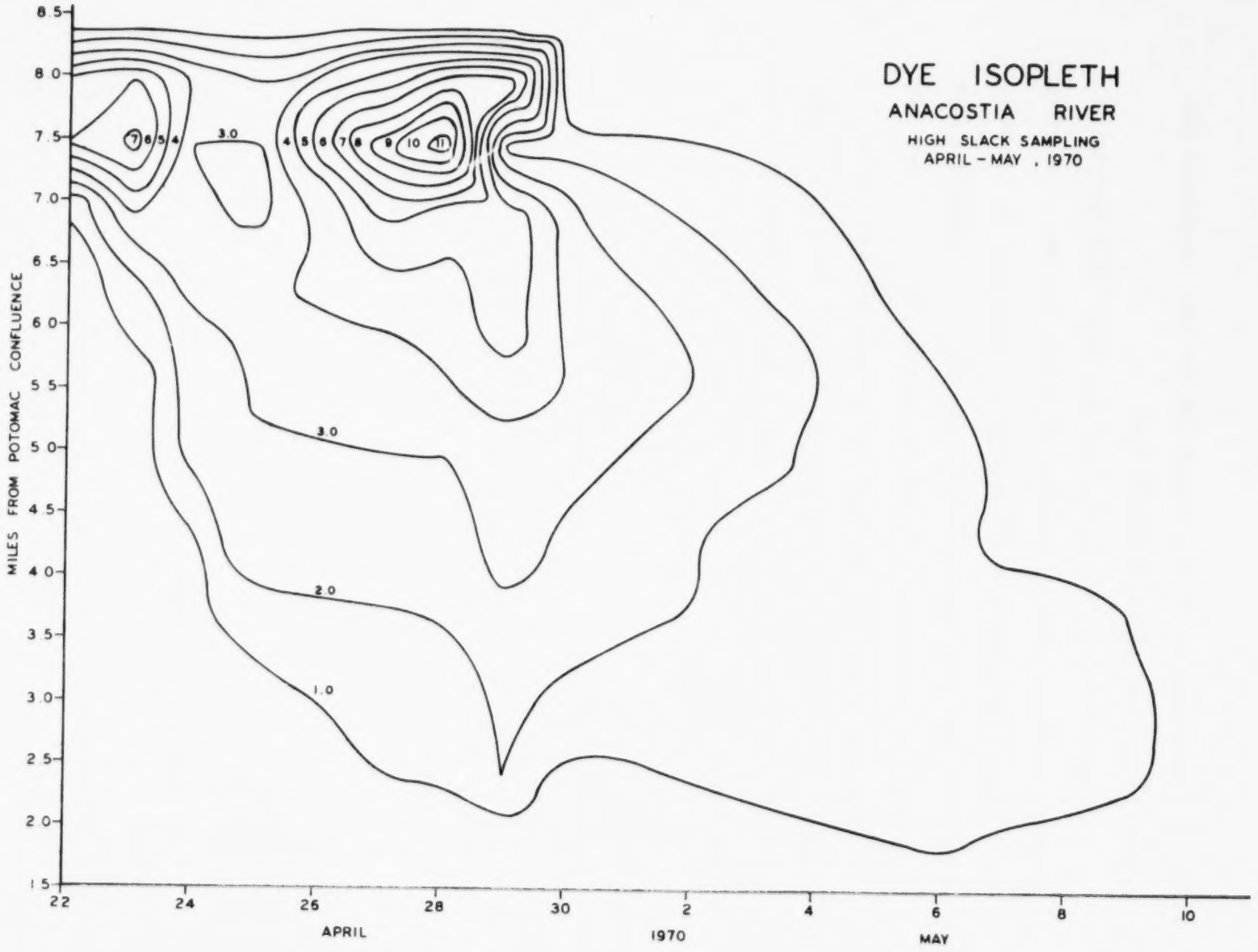

DYE ISOPLETH
ANACOSTIA RIVER
HIGH SLACK SAMPLING
APRIL - MAY , 1970
MILES FROM POTOMAC CONFLUENCE
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
7 6 5 4
3.0
4 5 6 7 8 9 10 11
3.0
2.0
1.0
22
24
26
28
30
2
4
6
8
10
APRIL
1970
MAY

FIGURE - A 12

# DYE ISOPLETH
## ANACOSTIA RIVER
LOW SLACK SAMPLING
APRIL – MAY , 1970

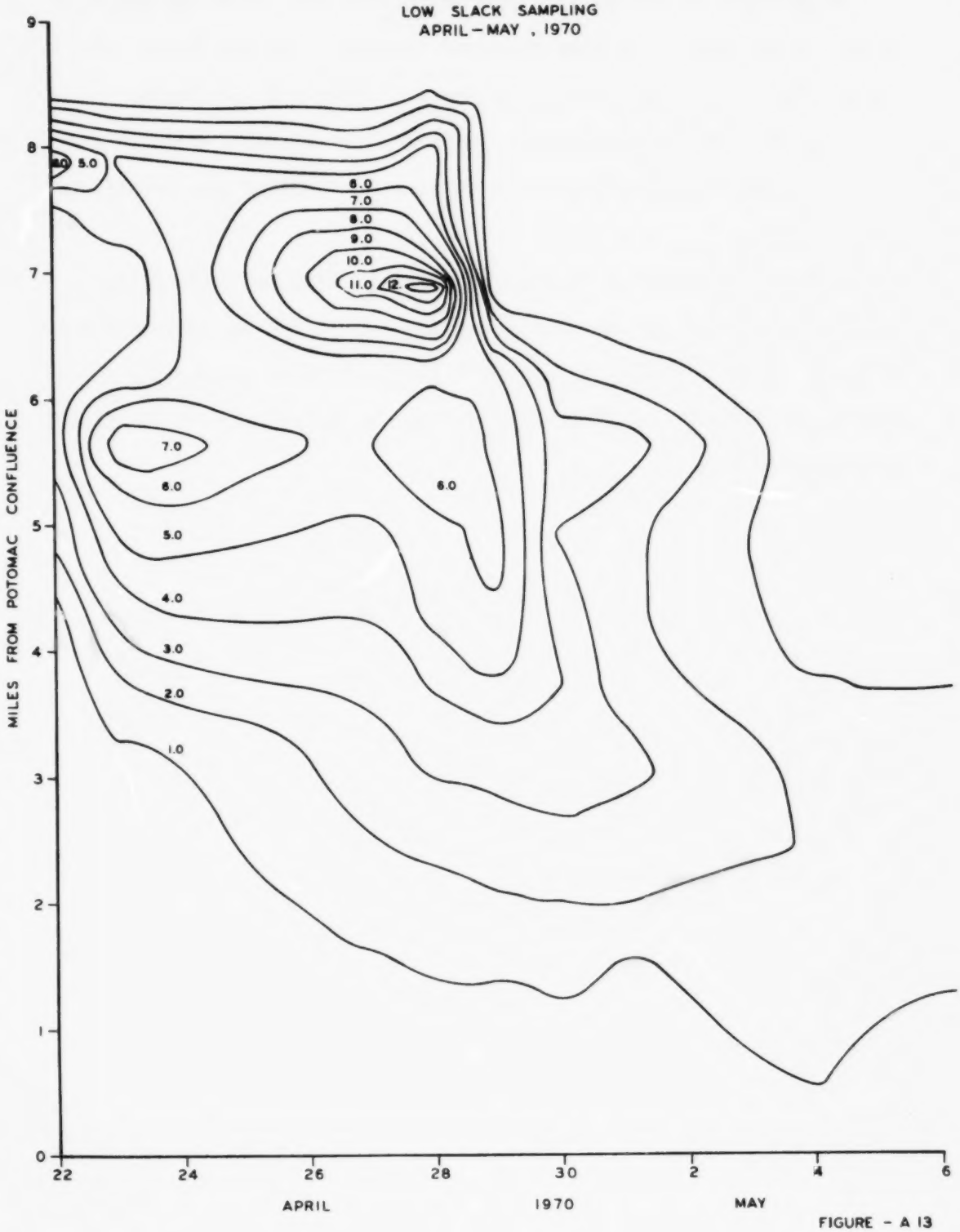



FIGURE - A 13

c. Loss Rate Determination

An estimate of the dye loss rate in the Anacostia River was obtained using a method similar to that discussed previously for the Potomac dye study. The total quantities of dye observed during a 25-day period following the release are shown in Figure 14. The dye loss rate for the Anacostia study which again followed first-order kinetics was computed to be 0.050/day.

Although 56 pounds of dye were discharged during the study period, the initial mass of dye observed in the Anacostia River was approximately 63 pounds. A relatively high natural background concentration (0.1 - 0.3 ppb) was measured prior to dye injection and may be responsible for this 7-pound difference.

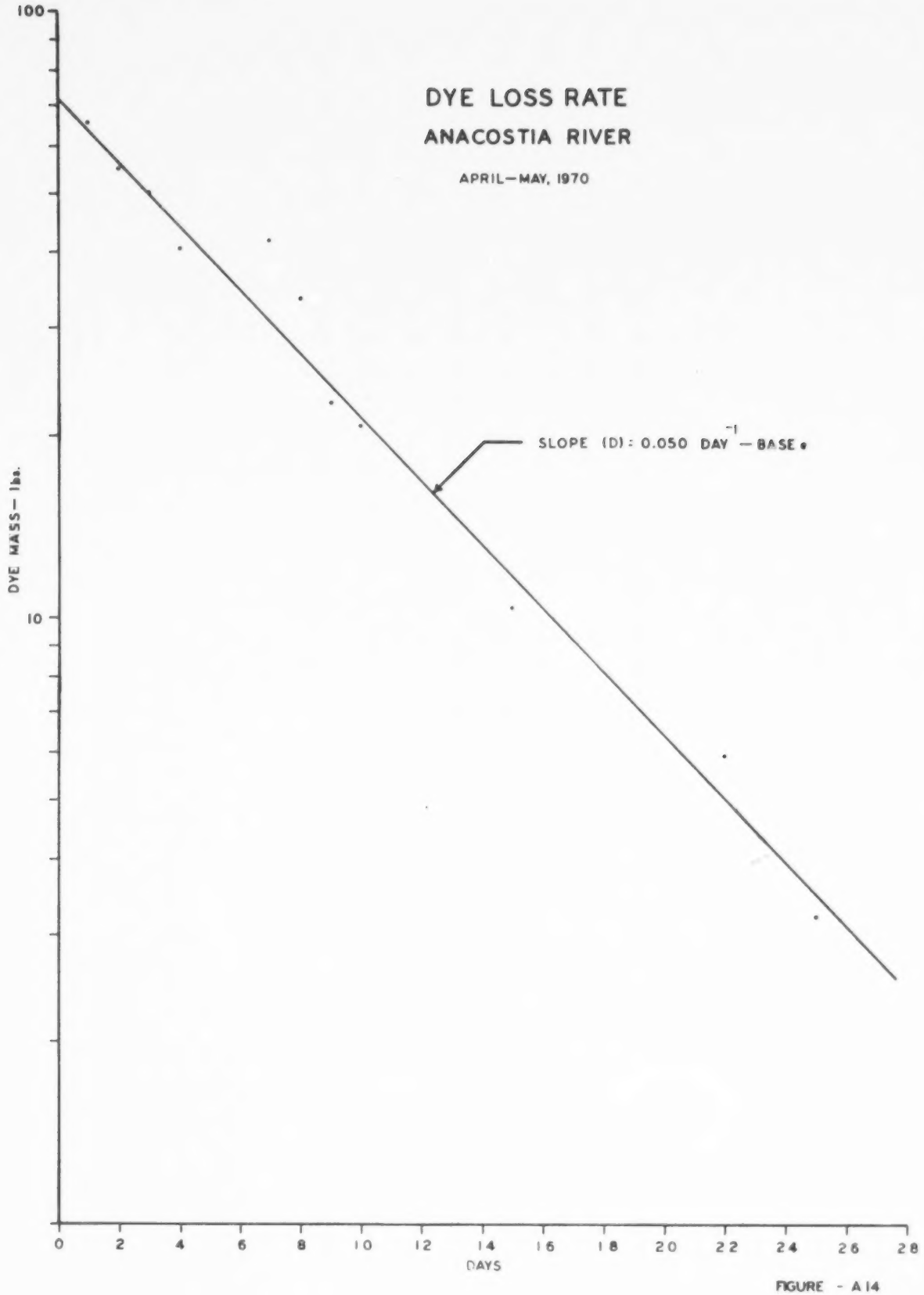

DYE LOSS RATE
ANACOSTIA RIVER
APRIL—MAY, 1970
SLOPE (D) = 0.050 DAY⁻¹ — BASE e
DYE MASS — lbs.
100
10
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DAYS

FIGURE - A 14

Table 4

Summary of Dye Concentration Data - Potomac Estuary - November 1959*

High Slack Tide Data

(ppb)

| Stations | 1 | 1A | 2 | 2A | 3 | 3E | 4 | 4A | 5 | 5A | 6 | 7 | 8 | 8A | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | |
| 11/03 | 0.01 | 0.10 | 0.07 | 0.02 | ---- | 1.39 | 0.98 | 0.33 | 0.20 | 0.20 | 0.10 | 0.01 | 0.19 | 0.08 | ---- | ---- | ---- |
| 11/08 | ---- | 0.01 | 0.01 | 0.01 | 0.01 | 0.40 | 0.80 | 0.80 | 1.17 | 0.71 | 0.52 | 0.36 | 0.12 | 0.03 | ---- | ---- | ---- |
| 11/10 | 0.13 | 0.14 | 0.15 | 0.19 | 0.64 | 0.88 | 0.80 | 0.80 | 0.81 | 0.86 | 0.82 | 0.82 | 0.55 | 0.24 | 0.20 | 0.21 | 0.20 |
| 11/12 | ---- | 0.01 | 0.13 | 0.02 | 0.29 | 0.55 | 0.53 | 0.45 | 0.66 | 0.66 | 0.56 | 0.50 | 0.15 | 0.11 | 0.03 | 0.04 | 0.14 |
| 11/14 | ---- | 0.03 | ---- | ---- | 0.15 | 0.70 | 1.07 | 0.56 | 0.58 | 0.63 | 0.60 | 0.49 | 0.20 | ---- | ---- | ---- | ---- |
| 11/17 | ---- | ---- | 0.01 | 0.02 | 0.03 | 0.07 | 0.15 | 0.22 | 0.28 | 0.50 | 0.59 | 0.36 | 0.39 | 0.39 | 0.25 | 0.16 | 0.02 |
| 11/19 | 0.02 | 0.03 | 0.04 | 0.02 | 0.06 | 0.13 | 0.15 | 0.24 | 0.31 | 0.46 | 0.54 | 0.61 | 0.50 | 0.38 | 0.31 | 0.22 | ---- |
| 12/01 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 0.01 | 0.02 | 0.10 | 0.20 | 0.21 | 0.24 | 0.26 | 0.12 |

* USGS dye analysis

Table 5
Summary of Dye Concentration Data - Potomac Estuary - November 1969*
Low Slack Tide Data
(ppb)

| Stations | 1 | 1A | 2 | 2A | 3 | 3A | 4 | 4A | 5 | 5A | 6 | 7 | 8 | 8A | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | |
| 11/03 | 0.22 | 0.02 | 0.02 | ---- | ---- | ---- | 0.12 | 0.10 | 0.16 | 0.32 | 0.35 | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 11/05 | 0.24 | 0.20 | 0.15 | 0.18 | 0.29 | 1.31 | 0.67 | 1.73 | 0.86 | 1.33 | 2.04 | 0.90 | 0.31 | ---- | ---- | ---- | ---- | ---- |
| 11/06 | 0.08 | 0.77 | 0.08 | 0.12 | 0.10 | 0.07 | 0.77 | 0.62 | 0.92 | 0.98 | 0.84 | 0.30 | ---- | ---- | ---- | ---- | ---- | ---- |
| 11/07 | 0.01 | ---- | ---- | 0.01 | 0.02 | 0.03 | 0.03 | 0.48 | 0.49 | 0.79 | 0.82 | 0.51 | 0.22 | 0.05 | 0.02 | 0.08 | ---- | ---- |
| 11/10 | ---- | ---- | ---- | 0.01 | 0.02 | 0.14 | 0.29 | 0.68 | 0.39 | 0.82 | 0.80 | 0.62 | 0.48 | 0.29 | 0.05 | 0.02 | 0.08 | ---- |
| 11/12 | 0.03 | 0.02 | 0.03 | 0.05 | 0.13 | 0.13 | 0.16 | 0.50 | 0.31 | 0.56 | 0.55 | 0.70 | 0.52 | 0.47 | 0.14 | 0.05 | 0.01 | ---- |
| 11/17 | ---- | 0.04 | ---- | 0.01 | 0.03 | 0.03 | ---- | 0.21 | 0.12 | 0.13 | 0.22 | 0.61 | 0.59 | 0.54 | 0.50 | 0.35 | 0.12 | ---- |
| 11/19 | 0.04 | 0.05 | 0.03 | 0.05 | 0.08 | 0.12 | 0.11 | 0.23 | 0.13 | 0.56 | 0.28 | 0.53 | 0.59 | 0.61 | 0.49 | 0.32 | 0.85 | ---- |
| 11/24 | ---- | ---- | 0.26 | 0.23 | 0.13 | 0.12 | 0.11 | 0.22 | 0.23 | 0.24 | 0.14 | 0.10 | 0.18 | 0.25 | 0.40 | 0.40 | 0.16 | 0.03 |
| 11/25 | ---- | ---- | 0.28 | 0.35 | 0.38 | 0.24 | 0.21 | 0.24 | 0.25 | 0.29 | 0.16 | 0.14 | 0.29 | 0.36 | 0.49 | 0.40 | 0.16 | 0.10 |

* USGS dye analysis

Table 6

Summary of Dye Concentration Data - Anacostia River - April-May, 1970
High Slack Tide Data
(ppb)

| Stations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | | |
| 4/22 | - | - | - | - | .14 | .14 | .13 | .14 | .14 | .15 | .16 | .21 | .23 | 1.15 | 6.0 | 5.3 | * | * | * |
| 4/23 | * | * | * | * | .12 | .16 | .15 | .16 | .20 | .35 | .60 | .74 | 1.45 | 4.05 | 7.2 | 6.1 | * | * | * |
| 4/24 | * | * | * | * | .13 | .24 | .21 | .34 | .80 | 1.00 | 2.10 | 2.30 | 3.20 | 3.20 | 3.0 | 3.8 | .11 | .11 | .13 |
| 4/25 | * | * | * | .12 | .28 | .28 | .39 | .78 | 1.50 | 3.70 | 2.80 | 3.20 | 3.90 | 2.80 | 3.0 | .3 | .11 | .13 | .10 |
| 4/27 | .28 | .24 | .21 | .22 | .74 | .52 | 1.00 | 1.25 | 2.00 | 2.30 | 2.95 | 3.30 | 4.60 | 6.10 | 9.6 | 5.0 | * | - | - |
| 4/28 | .14 | .14 | * | .17 | .35 | .52 | 1.19 | 1.19 | 2.19 | 2.13 | 2.97 | 4.00 | 4.67 | 5.45 | 11.3 | 7.7 | * | - | - |
| 4/29 | * | .31 | * | .26 | .41 | .70 | 2.01 | 2.29 | 2.80 | 3.54 | 3.33 | 4.81 | 5.62 | 5.80 | 1.8 | .7 | * | - | - |
| 4/30 | * | * | * | .19 | .22 | .61 | .92 | 1.82 | 2.34 | 2.83 | 3.33 | 3.96 | 3.78 | 3.33 | 1.7 | * | * | - | - |
| 5/06 | .11 | .20 | .15 | .41 | .78 | 1.08 | 1.47 | 1.54 | 1.50 | 1.19 | 1.30 | 1.00 | .54 | .30 | .2 | .1 | * | - | - |
| 5/07 | .23 | .24 | .16 | .52 | .68 | .96 | 1.34 | 1.36 | 1.22 | .89 | .88 | .69 | .48 | .19 | * | * | - | - | - |
| 5/12 | * | .21 | * | .25 | .35 | .44 | .68 | .70 | .68 | .61 | .56 | .45 | .34 | .25 | * | * | - | - | - |
| 5/22 | * | * | * | * | .11 | .14 | .17 | .20 | .20 | .21 | .23 | .21 | .20 | .19 | .2 | .2 | .14 | - | - |
| 5/27 | * | * | * | * | * | * | * | * | .12 | .12 | .19 | .18 | .20 | .20 | .2 | * | - | - | - |

* Less than .1

Table 7

Summary of Dye Concentration Data - Anacostia River - April-May, 1970
Low Slack Tide Data
(ppb)

| Stations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | | |
| 4/22 | * | * | .14 | .15 | .15 | .16 | .15 | .15 | .24 | .78 | 2.2 | 3.5 | 2.3 | 8.0 | 3.5 | 6.2 | * | * | * |
| 4/23 | * | * | .13 | .15 | .16 | .18 | .31 | .62 | 1.94 | 3.50 | 5.0 | 7.4 | 4.7 | 3.1 | 4.8 | 5.0 | .2 | .13 | .19 |
| 4/27 | .19 | * | .51 | .61 | .90 | 1.18 | 1.96 | 2.62 | 3.25 | 4.05 | 4.7 | 6.0 | 5.2 | 10.8 | 7.6 | 3.4 | * | - | - |
| 4/28 | .24 | .13 | .54 | .58 | 1.03 | 1.58 | 2.24 | 3.22 | 4.21 | 5.38 | 5.9 | 7.0 | 5.8 | 12.7 | 6.0 | 5.5 | 1.0 | - | - |
| 4/29 | .30 | .20 | .45 | .52 | 1.05 | 1.81 | 2.48 | 3.26 | 4.84 | 5.94 | 6.2 | 5.9 | 5.0 | .3 | .1 | * | * | - | - |
| 4/30 | .11 | .38 | .57 | .69 | 1.39 | 1.89 | 2.66 | 3.75 | 4.00 | 3.57 | 2.9 | 3.8 | 2.0 | .1 | * | * | * | - | - |
| 5/01 | * | .29 | .52 | .66 | .82 | 1.96 | 2.48 | 3.33 | 2.62 | 2.24 | 2.1 | 3.4 | 1.3 | .2 | .1 | .1 | - | - | - |
| 5/04 | .44 | .95 | .99 | 1.32 | 1.62 | 1.84 | 1.92 | 1.70 | 1.08 | .52 | .3 | .3 | .4 | .1 | * | * | .1 | - | - |
| 5/05 | .28 | .51 | .82 | .95 | 1.36 | 1.61 | 1.57 | 1.50 | .95 | .62 | .4 | .9 | .3 | .1 | * | * | 2.1 | - | - |
| 5/19 | .12 | .15 | .14 | .18 | .22 | .17 | .20 | .19 | .20 | .21 | .2 | .3 | .2 | .2 | .1 | .1 | - | - | - |

* Less than .1

# TRANSECT # 1 — KEY BRIDGE

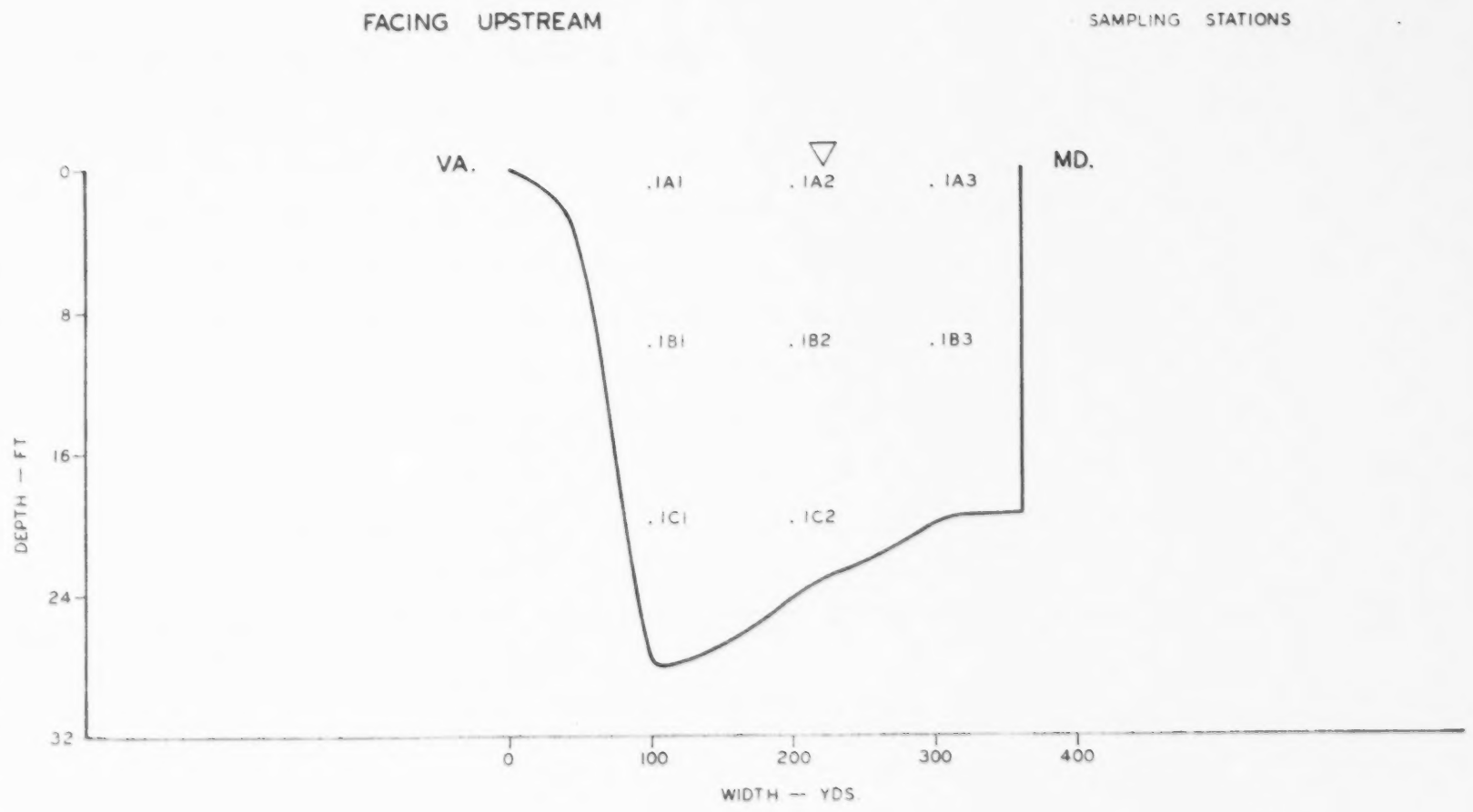



FIGURE A-15

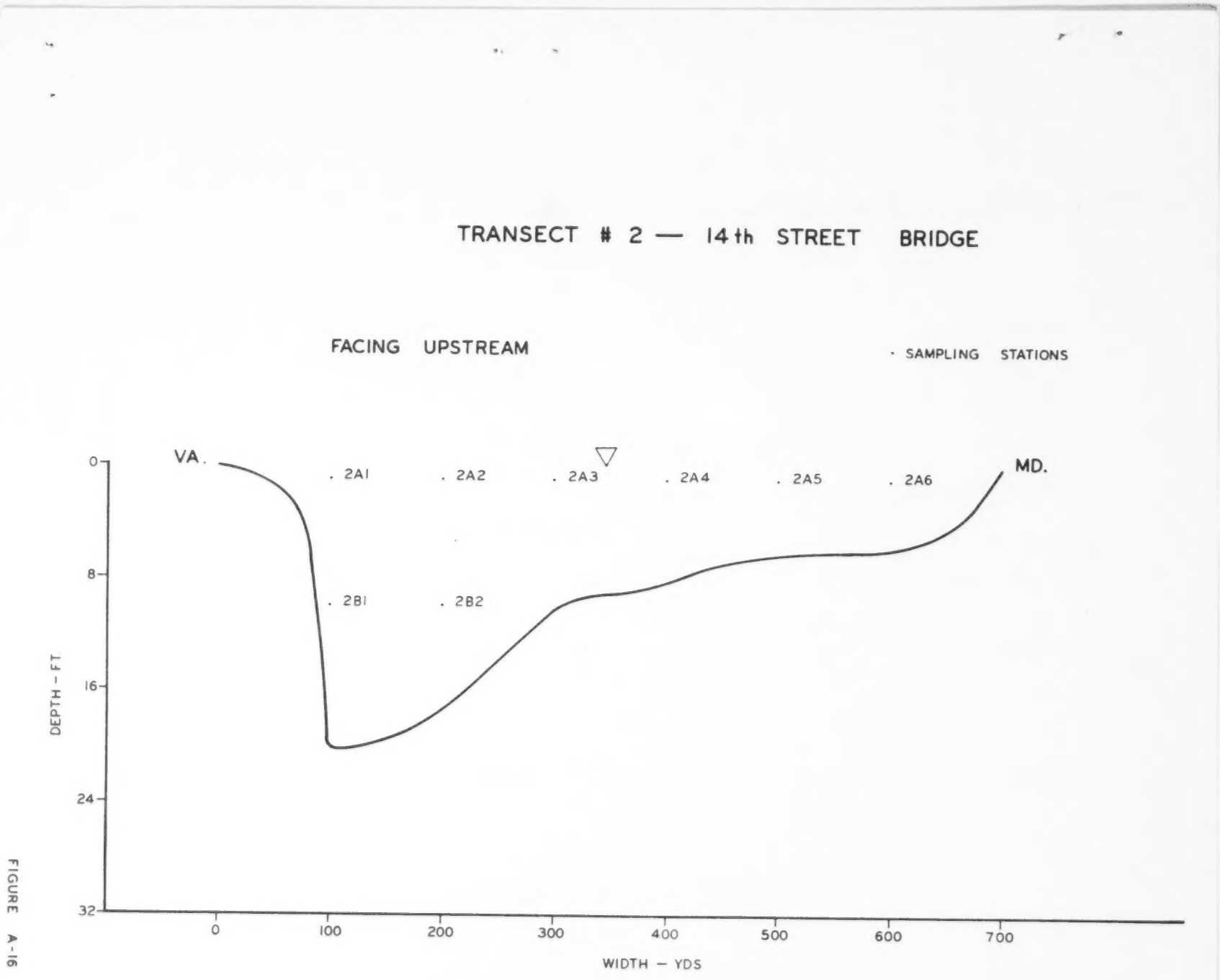

TRANSECT # 2 — 14th STREET BRIDGE
FACING UPSTREAM
· SAMPLING STATIONS
VA.
MD.
2A1
2A2
2A3
2A4
2A5
2A6
2B1
2B2
DEPTH - FT
0
8
16
24
32
0
100
200
300
400
500
600
700
WIDTH — YDS

FIGURE A-16

# TRANSECT # 3 — HAINS POINT

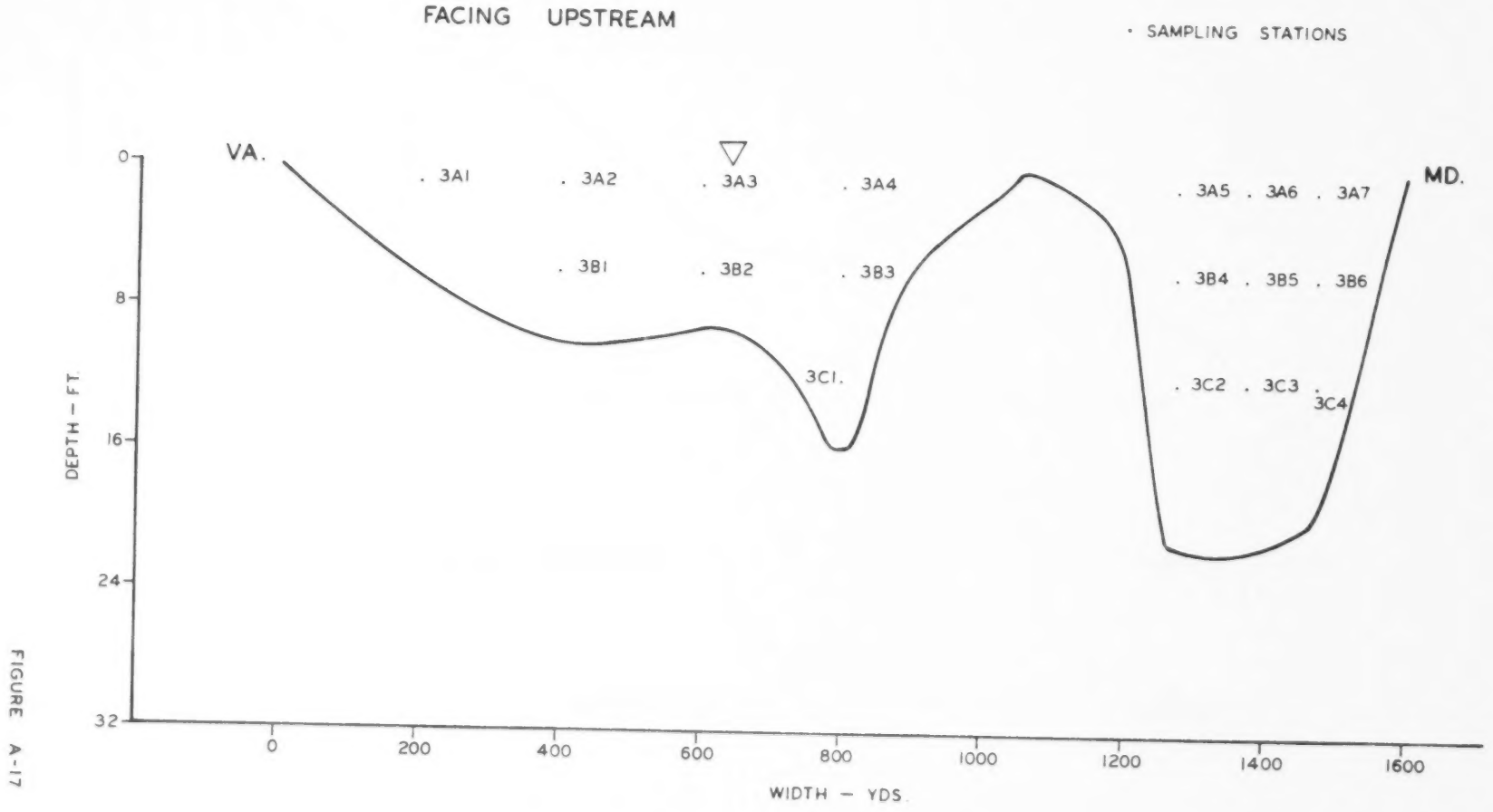



FIGURE A-17

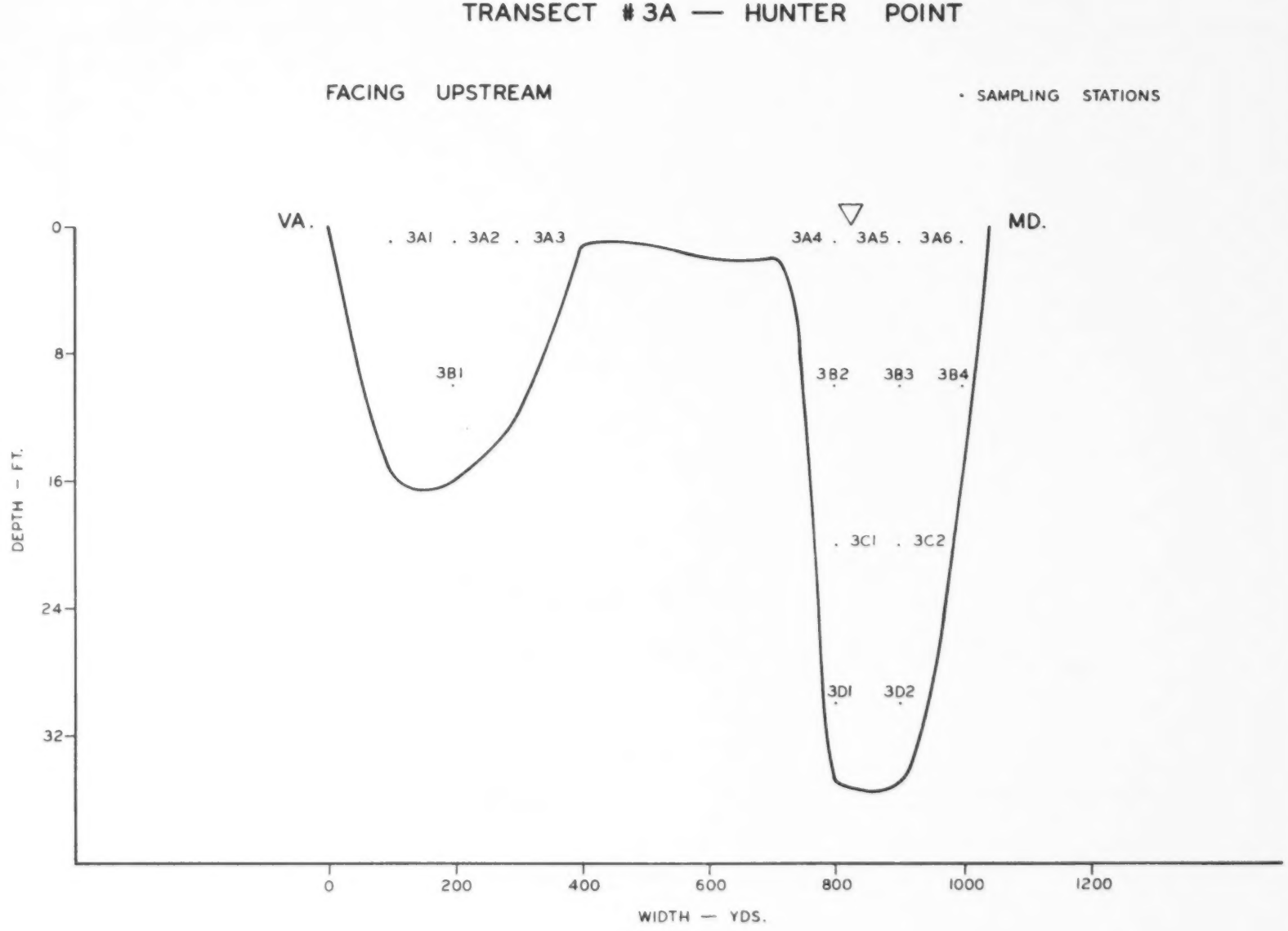

TRANSECT # 3A — HUNTER POINT
FACING UPSTREAM
· SAMPLING STATIONS
VA.
MD.
3A1
3A2
3A3
3A4
3A5
3A6
3B1
3B2
3B3
3B4
3C1
3C2
3D1
3D2
0
8
16
24
32
DEPTH — FT.
0
200
400
600
800
1000
1200
WIDTH — YDS.

FIGURE A-18

# TRANSECT # 4 — BELLEVUE

FACING UPSTREAM

· SAMPLING STATIONS

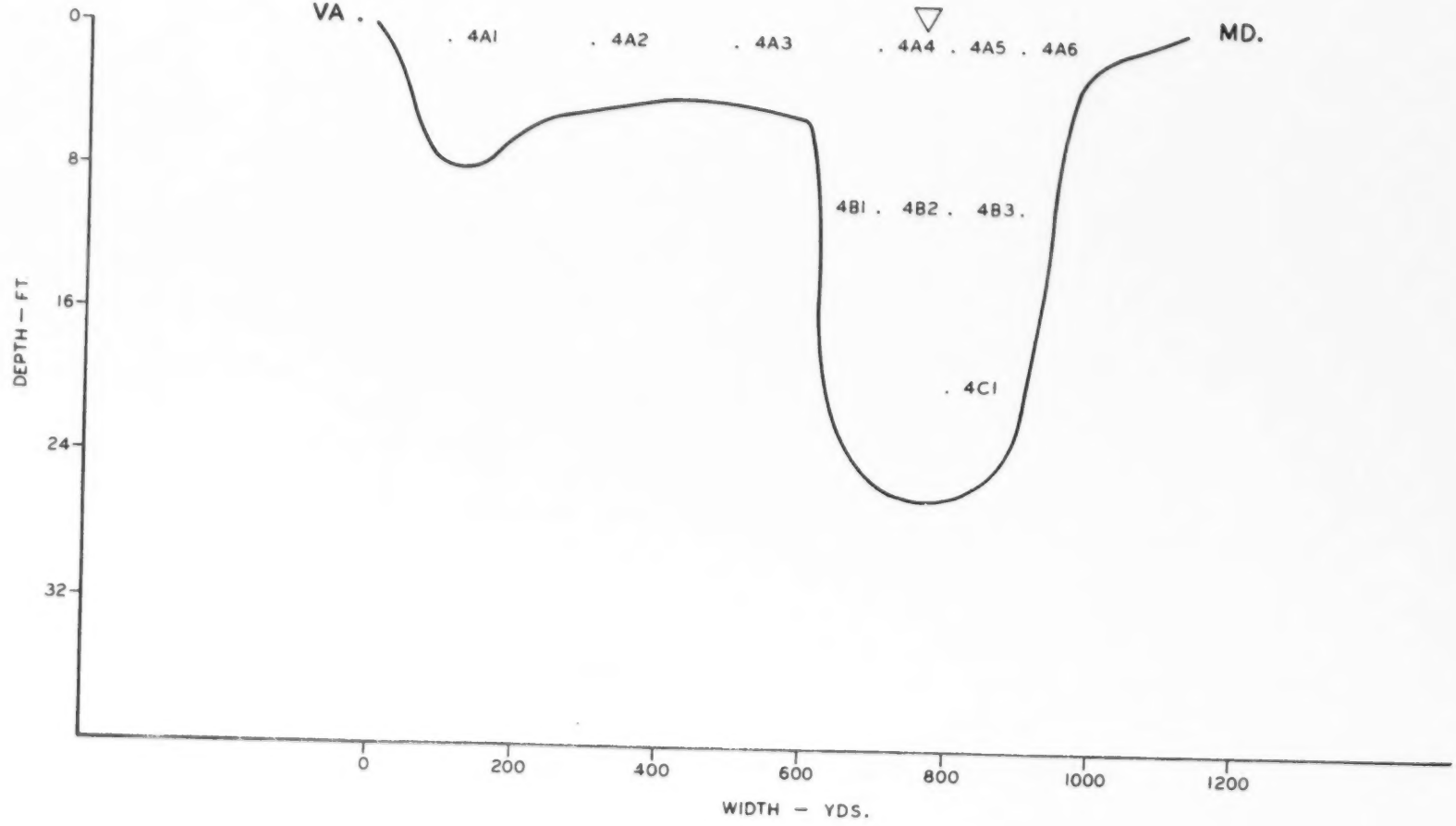



FIGURE A-19

## TRANSECT #4A — GOOSE ISLAND

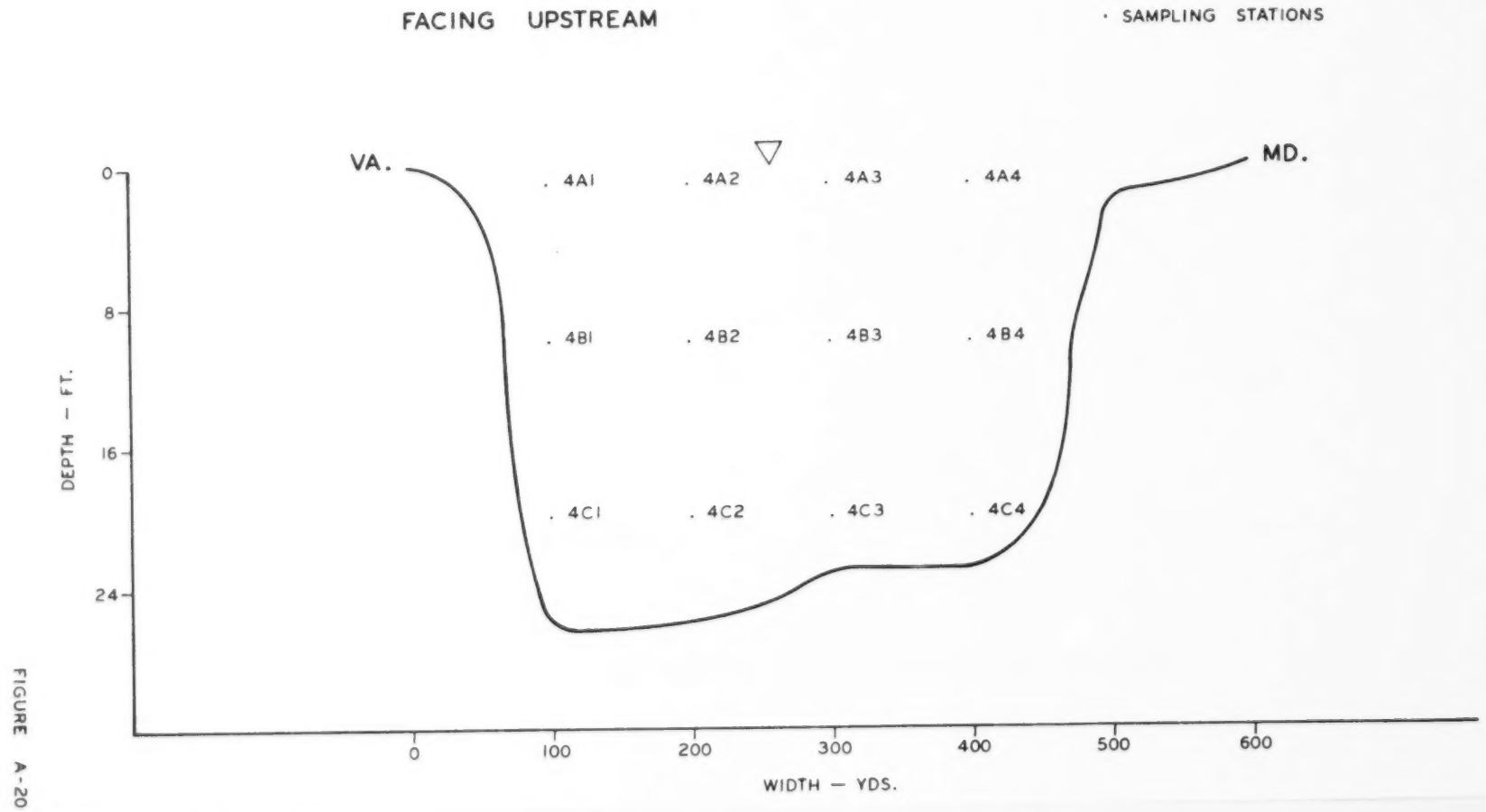



FIGURE A-20

# TRANSECT # 5 — WOODROW WILSON

FACING UPSTREAM

• SAMPLING STATIONS

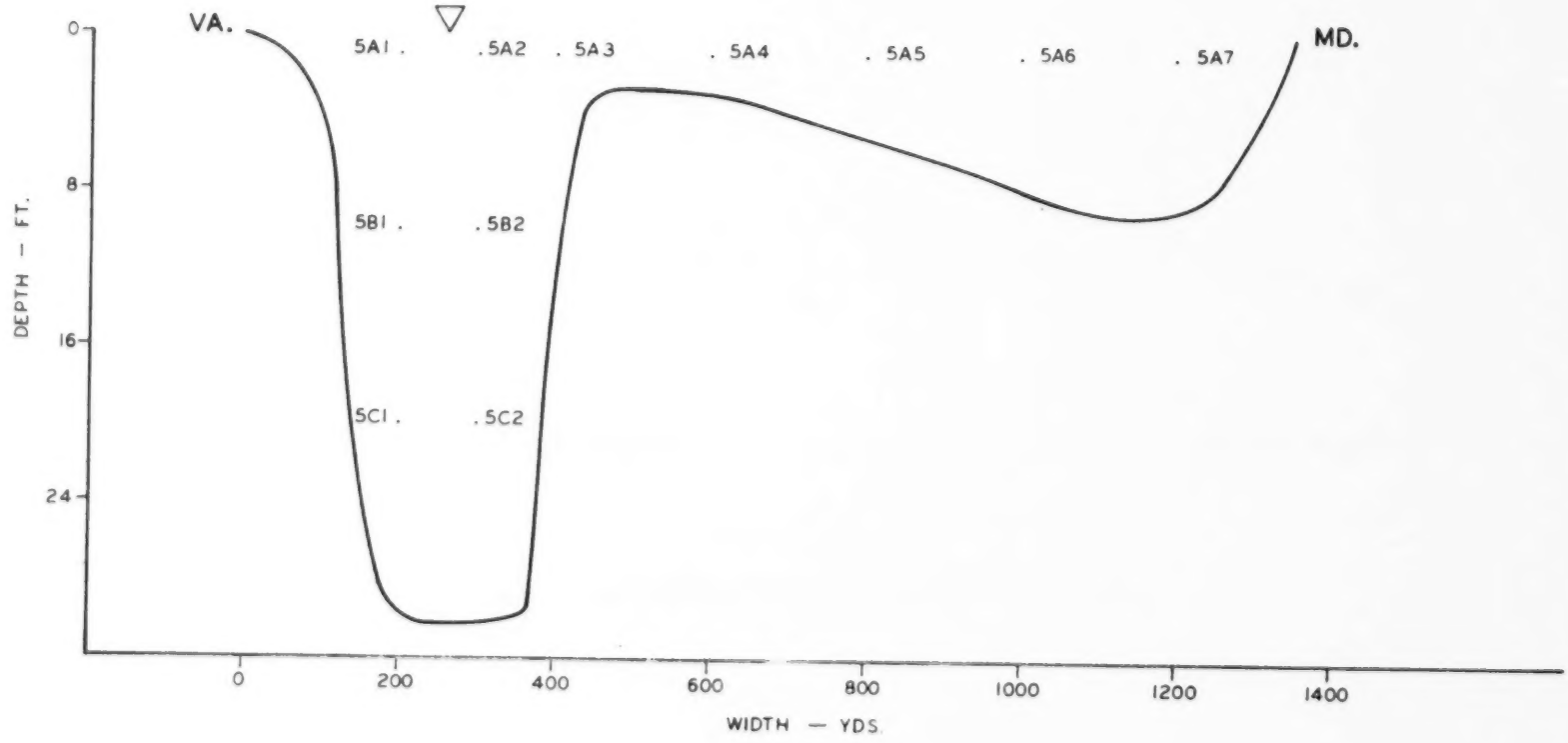



FIGURE A-21

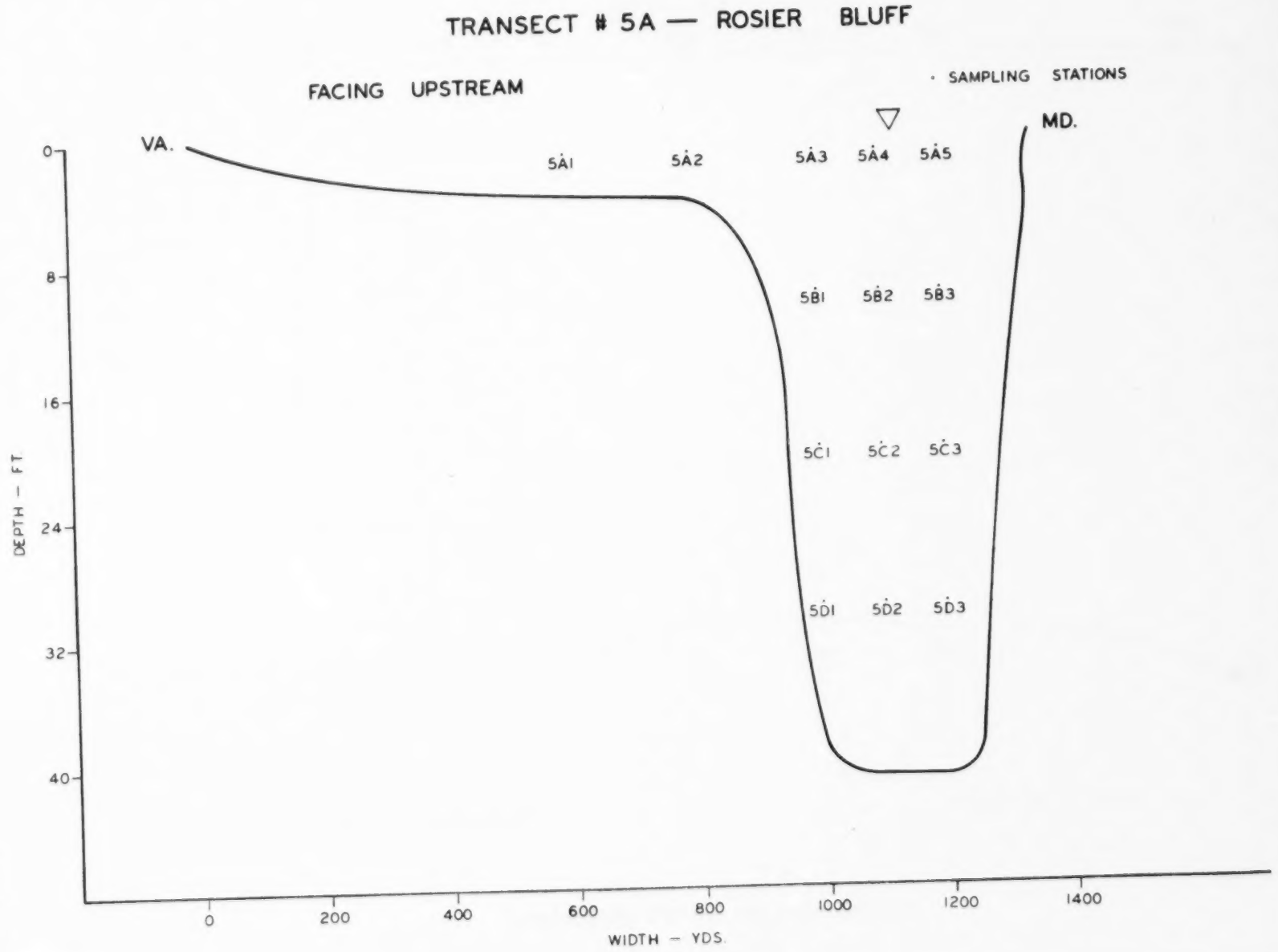

TRANSECT # 5A — ROSIER BLUFF
FACING UPSTREAM
· SAMPLING STATIONS
VA.
MD.
5A1
5A2
5A3
5A4
5A5
5B1
5B2
5B3
5C1
5C2
5C3
5D1
5D2
5D3
0
8
16
24
32
40
DEPTH — FT
0
200
400
600
800
1000
1200
1400
WIDTH — YDS.

FIGURE A-22

## TRANSECT #6 — BROAD CREEK

FACING UPSTREAM

· SAMPLING STATIONS

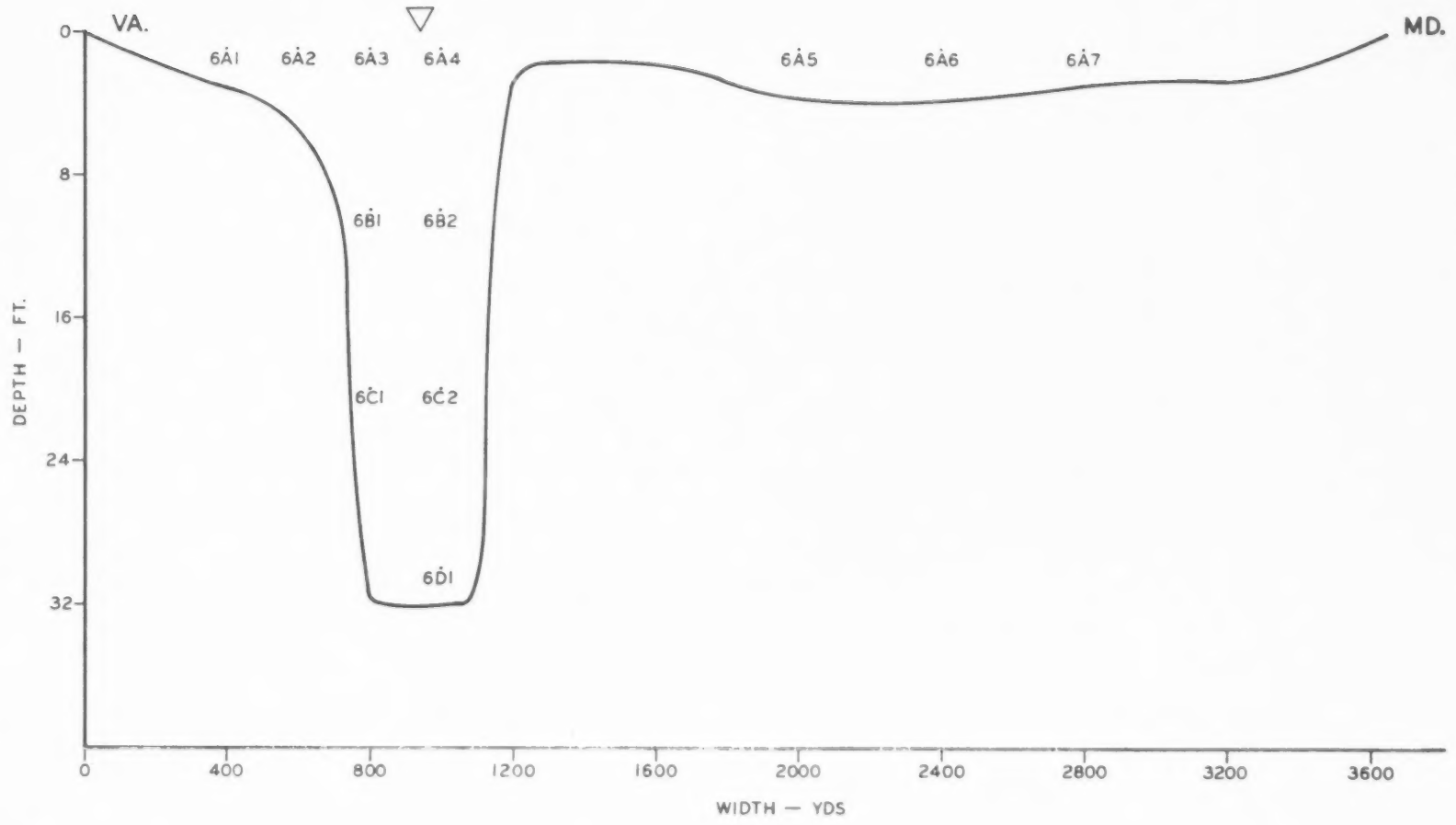



FIGURE A-23

# TRANSECT # 7 — PISCATAWAY CREEK

FACING UPSTREAM

• SAMPLING STATIONS

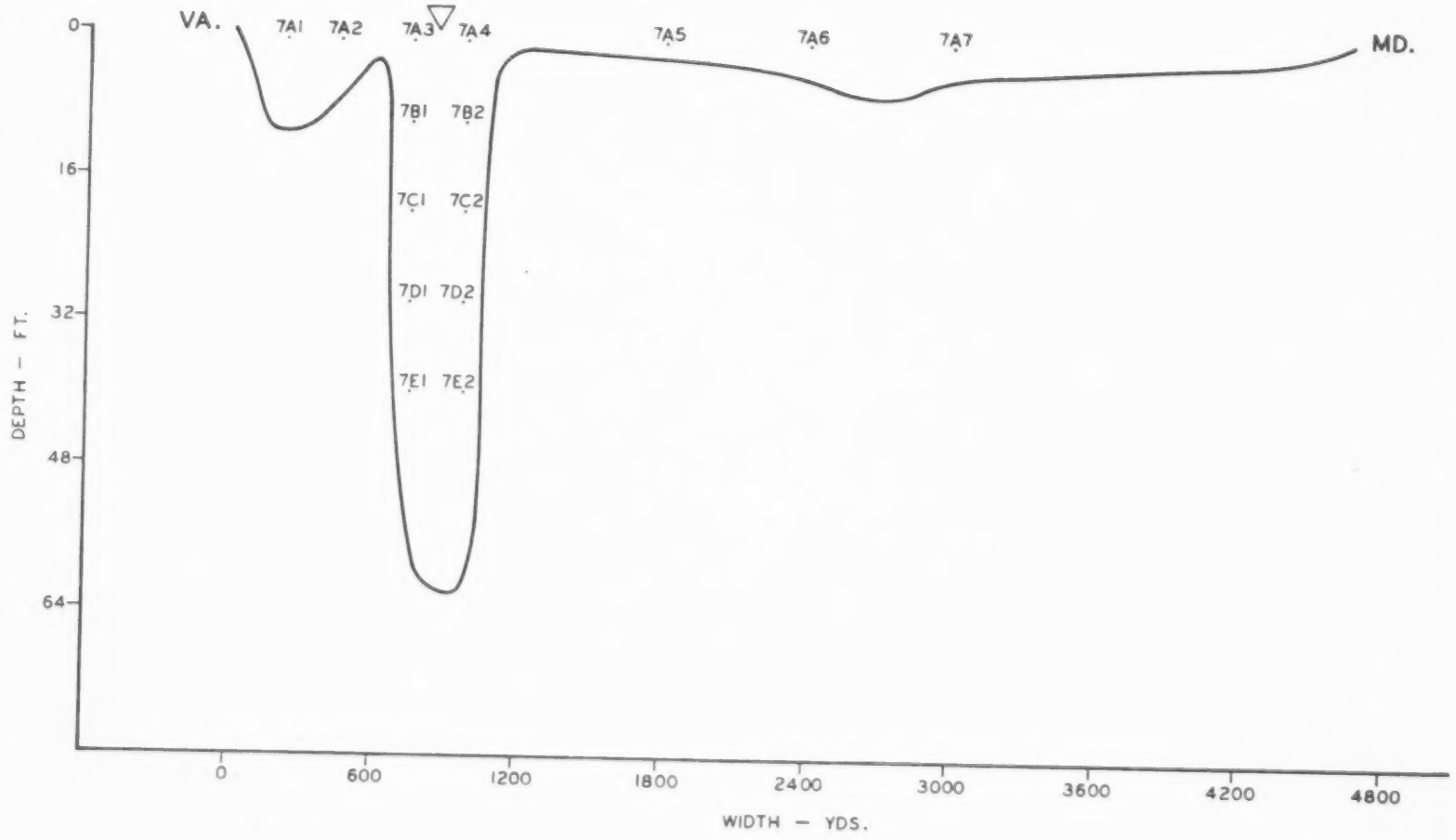



FIGURE A-24

# TRANSECT # 8 — DOGUE CREEK

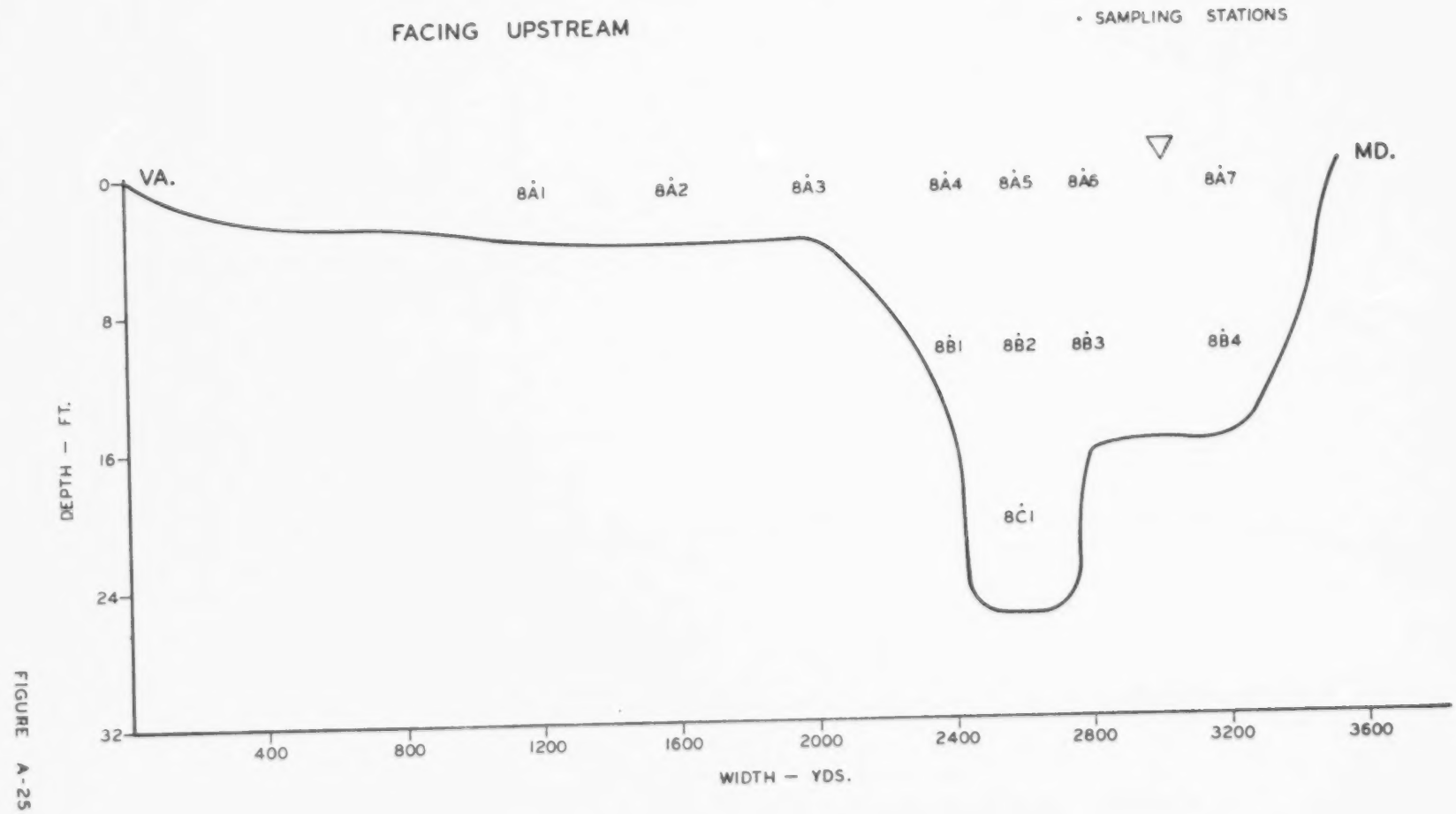



FIGURE A-25

# TRANSECT # 8A — GUNSTON COVE

FACING UPSTREAM

• SAMPLING STATIONS

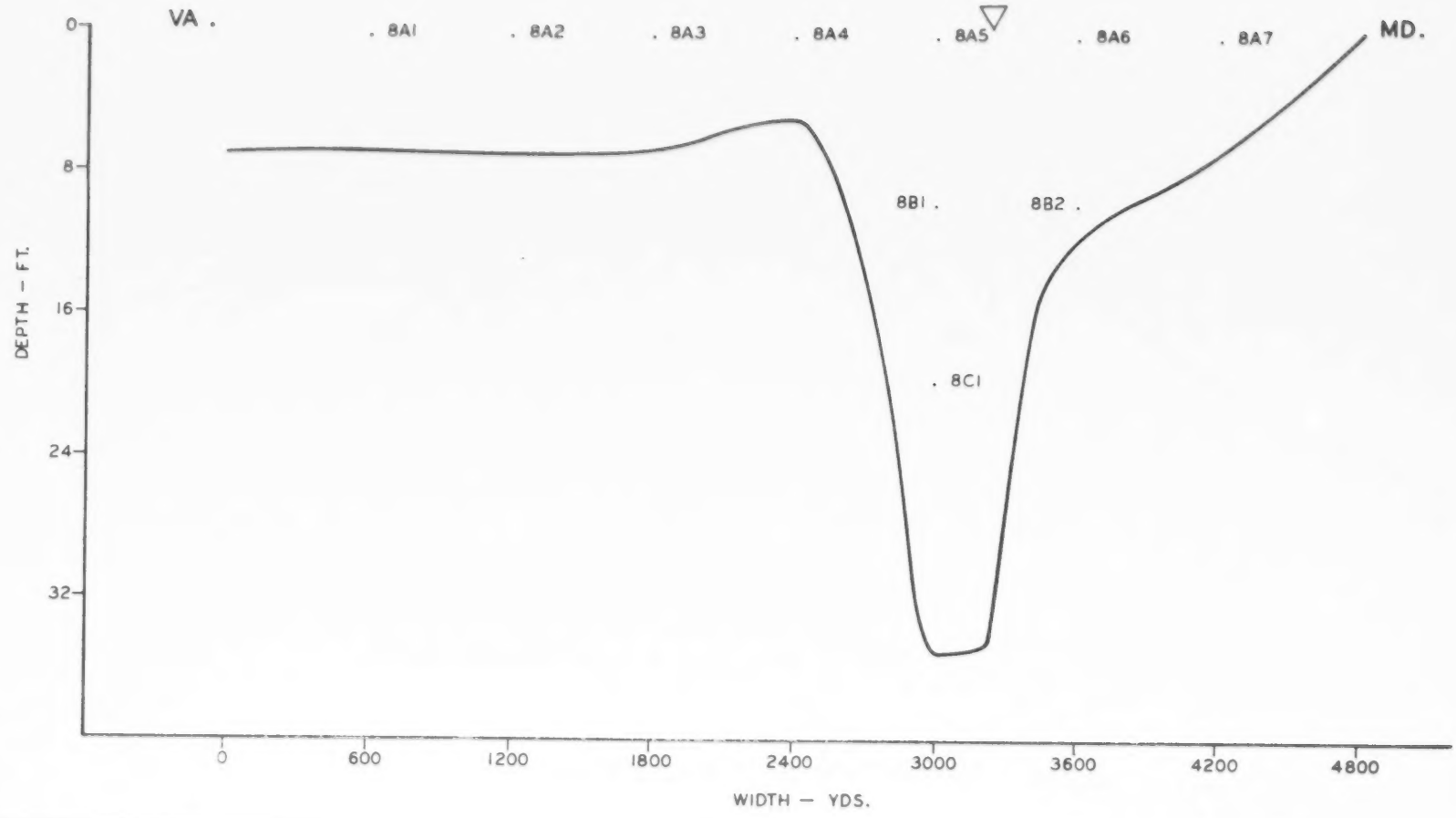



FIGURE A-26

## TRANSECT # 9 — HALLOWING POINT

FACING UPSTREAM

• SAMPLING STATIONS

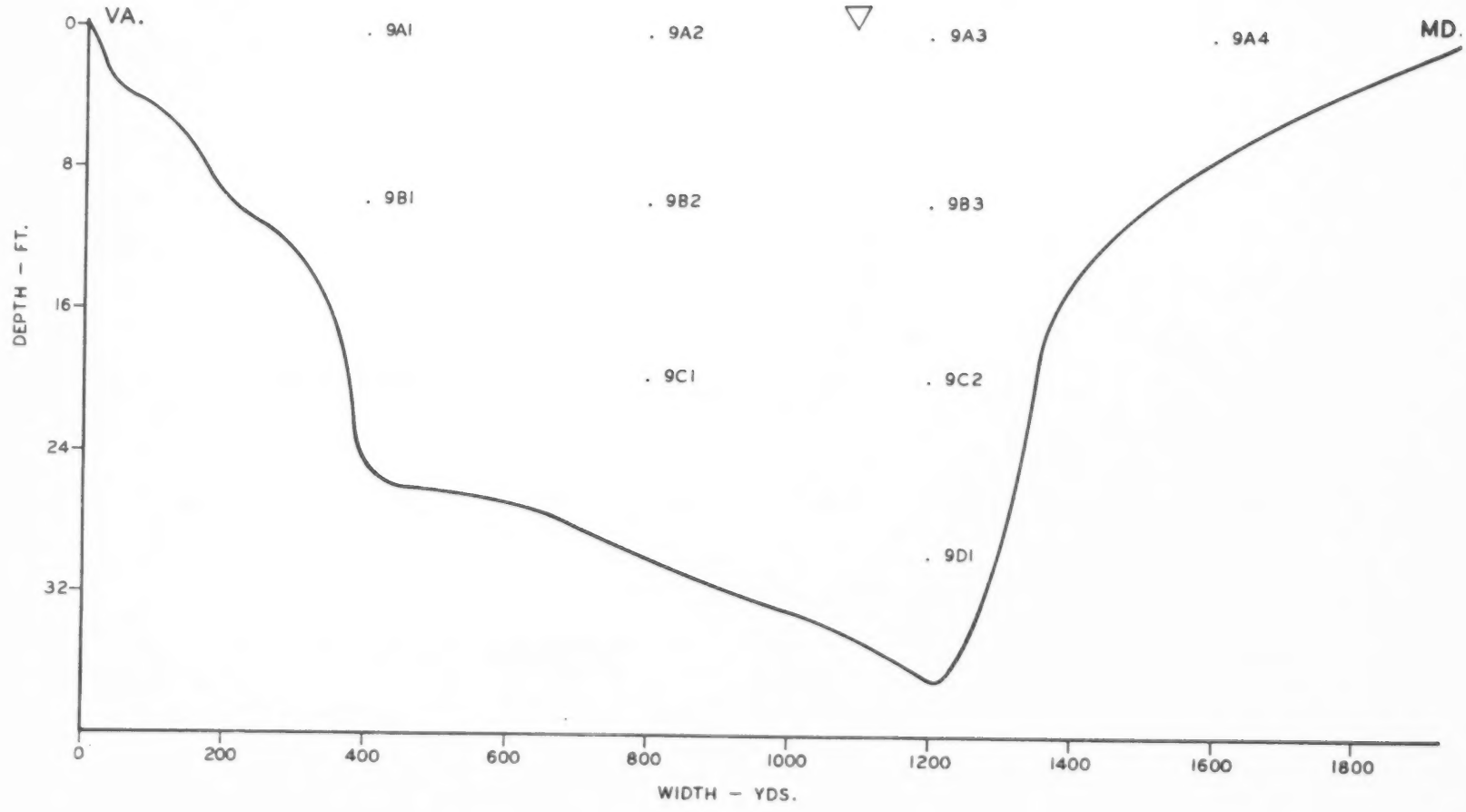



FIGURE A-27

# TRANSECT # 10 — INDIAN HEAD

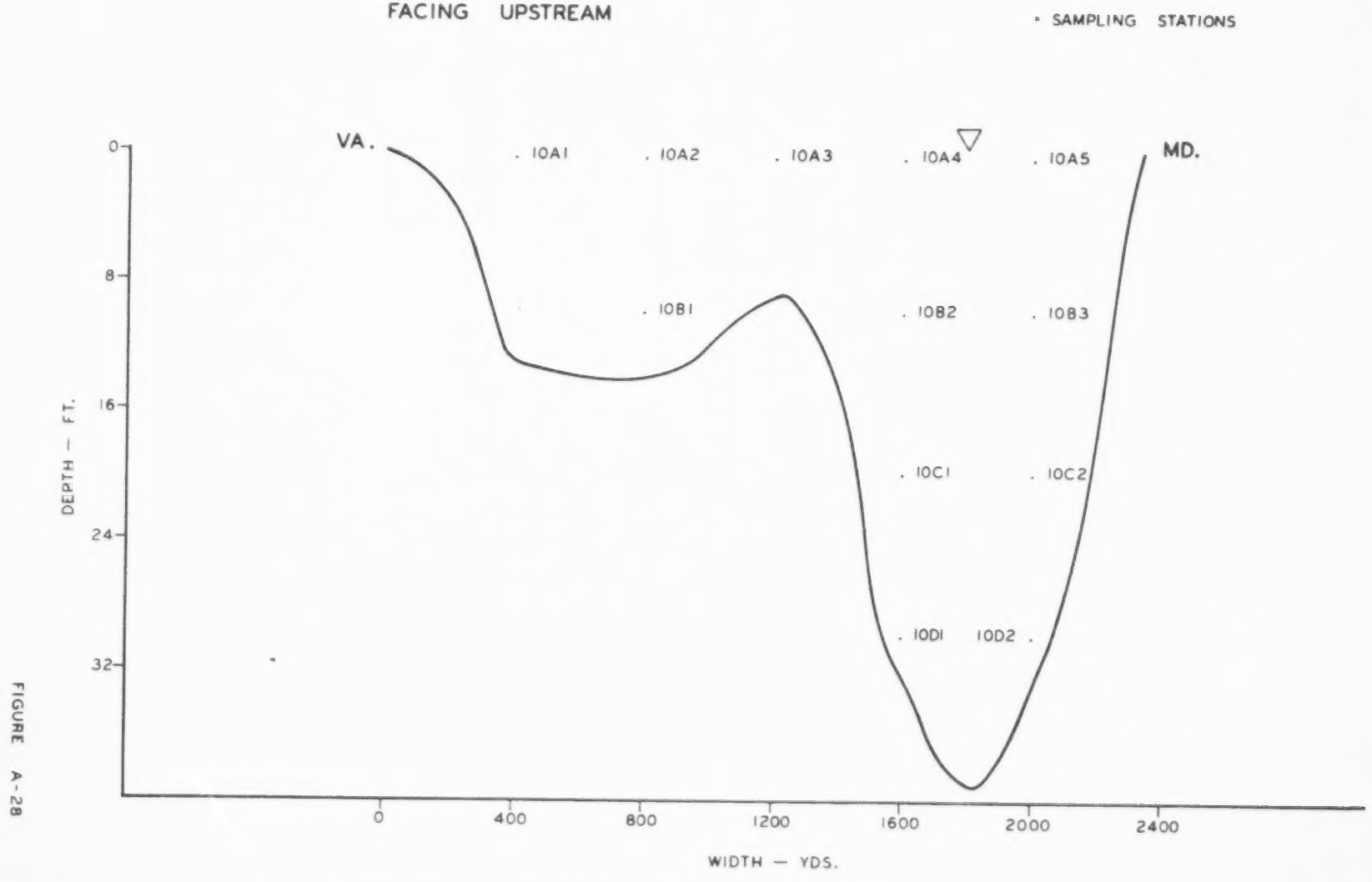



FIGURE A-28

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